

Technical Study 66e

# Water Disinfection by Solar Radiation

Assessment and Application

A. Acra, M. Jurdi, H. Mu'alleem,  
Y. Karahagopian, and Z. Raffoul

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# **Water Disinfection by Solar Radiation**

**Assessment and Application**

by

**A. Acra, M. Jurdi, H. Mu'Allem,  
Y. Karahagopian, and Z. Raffoul**



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## Abstract

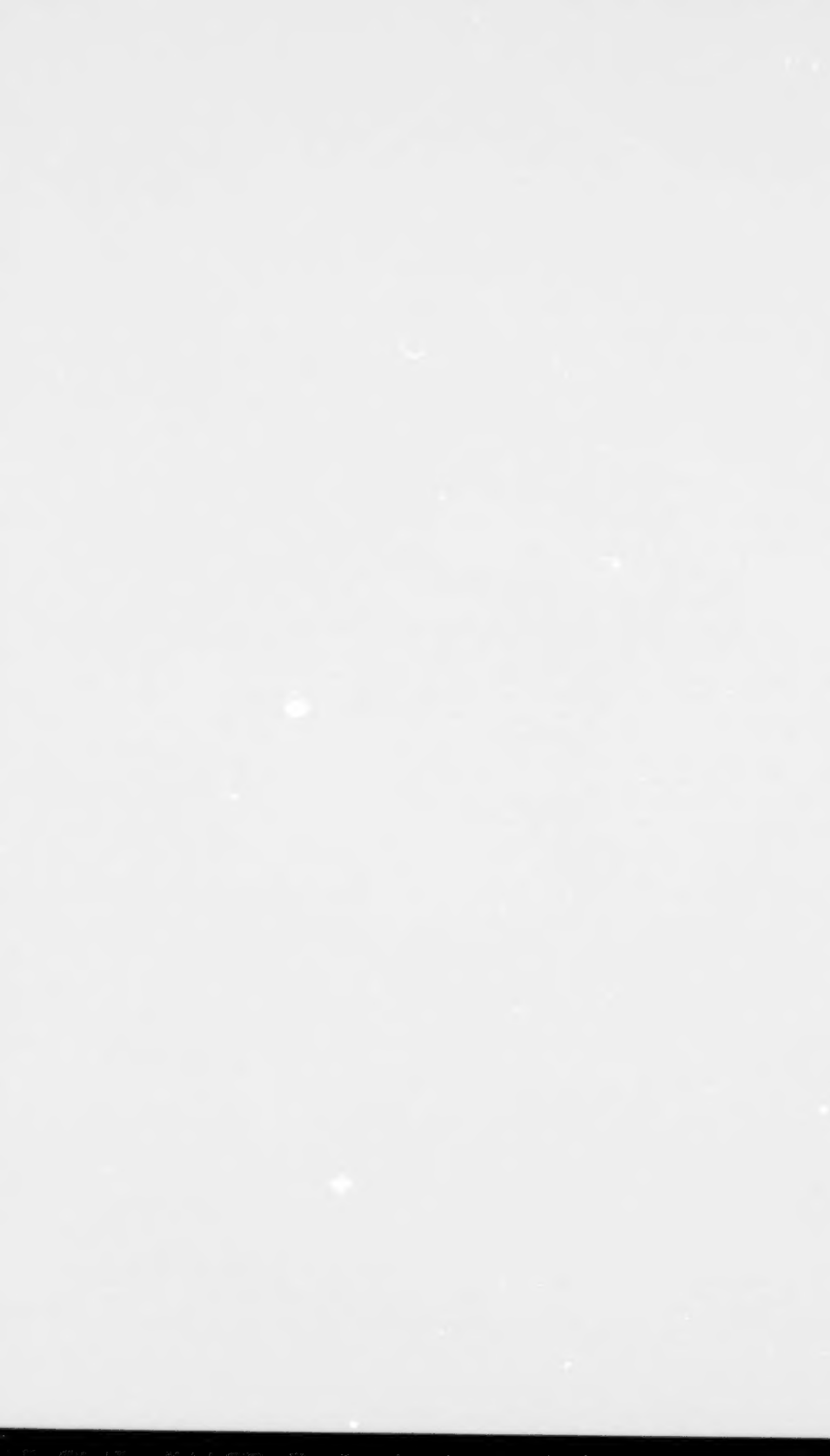
This publication is aimed at researchers, primary health care workers, and technical workers interested in solar energy applications and drinking-water disinfection. It provides basic information on solar energy, covering especially its ultraviolet (UV) component. Aspects such as the transmission of solar radiation through the atmosphere and different media (glass, water, plastics, etc.), its world distribution, and the experimental monitoring of UV radiation in Beirut (Lebanon) are thoroughly discussed. The main water disinfection methods are reviewed and continuous-flow solar systems are explained. These were tested on two types of pilot plants ("solar reactors"), based on the biocidal characteristics of either solar energy alone or halogens in combination with solar radiation ("halosol" system). The experimental results are discussed in detail, covering the kinetics of the processes, design of the reactors, and their performance in terms of bacterial survival and solar dechlorination.

## Résumé

Cette publication est destinée aux chercheurs, travailleurs en soins de santé primaires et techniciens qui s'intéressent aux applications de l'énergie solaire à la désinfection de l'eau de boisson. Elle offre des informations de base sur l'énergie solaire, particulièrement les rayons ultraviolets. La transmission des radiations solaires dans l'atmosphère et dans d'autres milieux (verre, eau, plastiques, etc.), ainsi que la répartition de ces radiations dans le monde et l'expérience tentée à Beyrouth (Liban) de contrôler la radiation ultraviolette y sont traitées abondamment. Les principales méthodes de désinfection de l'eau sont exposées et les systèmes solaires continus expliqués. Les uns et les autres ont été éprouvés dans deux types d'usines pilotes («réacteurs solaires») appliquant les propriétés biocides de l'énergie solaire seule ou combinée aux halogènes (système «halosol»). Les auteurs présentent par le menu les résultats de l'expérience, abordant la cinétique des procédés, le modèle des réacteurs et la performance de ces derniers mesurée en termes de survie des bactéries et de déchloration solaire.

## Resumen

Esta publicación está dirigida a investigadores y técnicos interesados en las áreas de energía solar y desinfección de agua potable. Se presenta información básica sobre energía solar, especialmente en lo relacionado a la radiación ultravioleta (UVR). Se discuten detalladamente aspectos como la transmisión de radiación a través de la atmósfera y de diferentes medios (vidrio, agua, plásticos, etc.), su distribución mundial y la medición experimental de UVR en Beirut (Libano). Se hace una revisión crítica de los principales métodos de desinfección de agua, para luego explicar en detalle los sistemas solares de flujo continuo. Estos fueron probados en dos tipos de plantas piloto ("reactores solares"), basados en las características biocidas de la radiación solar únicamente, o en combinación con halógenos (sistema "halosol"). Los resultados experimentales se discuten en detalle, cubriendo la cinética de los procesos, el diseño de los reactores y su desempeño en términos de destrucción bacteriana y eliminación solar de residuos de cloro.



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## Foreword

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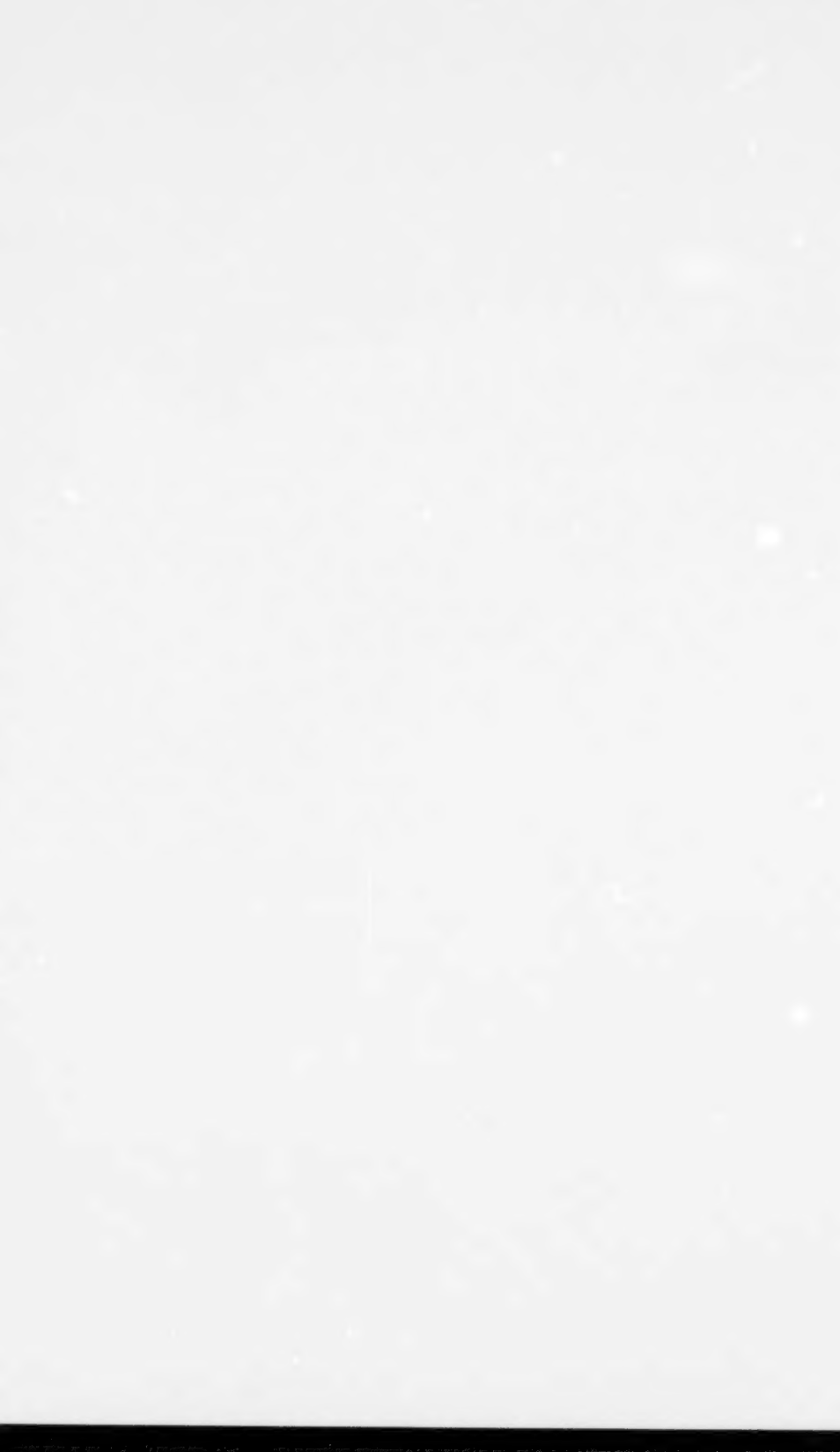
Using solar radiation to disinfect water is not a new idea, although its application has been limited. Motivated by ancient disinfection practices still being used in several places in the world, and related indications found in old books, Prof. Afim Acra of the American University of Beirut (Lebanon) initiated during the late 1970s research on the effect of solar radiation on the quality of water used in oral rehydration solution. The initial research project was financially supported by the Gulbenkian Foundation (Lisbon, Portugal) and the United Nations Children's Fund (UNICEF). This experience was followed by a project funded by IDRC (International Development Research Centre), in which Prof. Acra and his team examined the effectiveness of a continuous-flow solar disinfection unit in eliminating pathogenic organisms from water. This system was intended for use by small communities, refugee camps, institutions, and during emergency and disaster situations.

In the early 1980s, and based on the pioneering work of Prof. Acra, the Integrated Rural Energy Systems Association (INRESA), an associated program of the United Nations University (UNU), supported several other research projects on solar water disinfection. Their preliminary findings confirmed those of Prof. Acra's experience, that ground and surface water can be disinfected of many kinds of bacterial pathogens through solar radiation.

In August 1988, IDRC and UNU cosponsored the first Workshop on Solar Water Disinfection. The workshop was hosted by the Brace Research Institute in Ste Anne de Bellevue (Quebec, Canada), which serves as the secretariat for INRESA. The original comprehensive technical report filed by Prof. Acra on completion of his IDRC-supported research project was presented at the workshop. This book is an edited version of that report.

It is hoped that researchers and field-workers alike will use Prof. Acra's findings to continue research and development in the field of solar disinfection of water meant for human consumption.

**Alex Redekopp**  
Senior Program Officer (formerly)  
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## Preface

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The first two sections of this publication familiarize the reader with certain characteristics of solar radiation and its environmental and ecological impact, knowledge that is essential for photobiologists and photoecologists. We hope that it will provide valuable practical information and guidelines to benefit environmentalists and scientists engaged in the various aspects of photobiology in developing countries. The main emphasis, however, is on natural ultraviolet (UV) radiation, its role as a biocidal agent, and the monthly distribution of UV-A intensity as it prevails throughout the year in Beirut, Lebanon.

The following sections are devoted to water disinfection and the development and assessment of a prototype facility with suitably designed "solar reactors" intended for experimentation on the photodecontamination of drinking water on a continuous-flow basis. In the event of its success after convincing field trials, this simple technology could then be transferred to developing countries, where solar energy prevails in abundance. Small rural communities, refugee and recreational camps, and institutions in remote areas would be some of the potential beneficiaries.

Much of the basic information and principles involved in the development of this system has been derived from previous research on the solar decontamination of water exposed to sunlight in transparent glass or plastic containers. The ultimate aim in this case was to provide water at the household level in rural communities deprived of safe drinking water. The study on the combined treatment of water with halogens and solar exposure, herein referred to as "halosol," forms another aspect of the research project supported by IDRC.

We hope that researchers elsewhere will endeavour to verify our findings and further develop the proposed water-disinfection systems to a practicable level for transfer to developing countries. Indeed, this would be a desirable contribution to the International Drinking Water Supply and Sanitation Decade.

A. A.  
American University of Beirut



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*This book is dedicated to the children of the  
world, so that they may have life, and have it  
more abundantly.*



Solar radiation is becoming increasingly appreciated because of its influence on living matter and the feasibility of its application for useful purposes. It is a perpetual source of natural energy that, along with other forms of renewable energy, has a great potential for a wide variety of applications because it is abundant and accessible. Solar radiation is rapidly gaining ground as a supplement to the nonrenewable sources of energy, which have a finite supply.

Recent developments in the areas of photochemistry and photobiology have also helped in bringing attention to solar radiation. The significant depletion of the stratospheric ozone layer, which shields the earth from much of the biologically injurious solar ultraviolet radiation (UVR), is apparently due to human activity and has now become a popular topic. Adverse biological effects of UVR on man include, among others, sunburn (erythema), conjunctivitis, and skin cancer (WHO 1979). In contrast, the vital phenomenon of photosynthesis is an example of the beneficial effects of sunlight in the natural environment. Other beneficial and harmful effects on a variety of living beings, especially microorganisms, are well documented (Jagger 1976; Chamberlin and Mitchell 1978; Harm 1980; Senger 1980). Solar radiation has, therefore, a prominent ecological role.

Most photobiological investigations have been confined to laboratory work based on the use of monochromatic UVR produced artificially. Because these model studies do not completely reflect the natural situation, the recent trend is to supplement them with experimental work employing sunlight as a natural UV source. This gives results with more realistic, practical values. However, the polychromatic nature of solar radiation, its variable intensity, and the limited knowledge of its distribution at the local level tend to hamper such efforts and complicate the interpretation of the results.

## The solar radiation spectrum

The electromagnetic radiation emitted by the sun shows a wide range of wavelengths. It can be divided into two major regions with respect to the capability of ionizing atoms in radiation-absorbing matter: ionizing radiation (X-rays and gamma-rays) and nonionizing radiation (UVR, visible light, and infrared radiation). Fortunately, the highly injurious ionizing radiation does not penetrate the earth's atmosphere.

Solar radiation is commonly divided into various regions or bands on the basis of wavelength (Table 1). Ultraviolet radiation is that part of the electromagnetic spectrum between 100 and 400 nm. It is, in turn, divided rather arbitrarily from the viewpoint of its biological effects into three major components (Fig. 1).

Table 1. Spectral bands of incoming solar energy and atmospheric effects.

| Spectral band    | Wavelength limits (nm) <sup>a</sup> | Atmospheric effects                                                                                       |
|------------------|-------------------------------------|-----------------------------------------------------------------------------------------------------------|
| Gamma rays       | <0.03                               | Absorbed by the upper atmosphere                                                                          |
| X-rays           | 0.03–3                              | Absorbed by the upper atmosphere                                                                          |
| Ultraviolet (UV) |                                     |                                                                                                           |
| Extreme UV       | 3–200                               | Absorbed by the upper atmosphere                                                                          |
| UV-C             | 200–280                             | Absorbed by the upper atmosphere                                                                          |
| UV-B             | 280–320                             | Mostly absorbed by oxygen, nitrogen, and ozone in the upper atmosphere                                    |
| UV-A             | 320–400                             | Transmitted with severe atmospheric scattering                                                            |
| Visible          | 400–700                             | Transmitted with moderate atmospheric scattering of shorter wavelengths                                   |
| Infrared (IR)    |                                     |                                                                                                           |
| Reflected IR     | 700–3 000                           | Mostly reflected                                                                                          |
| Thermal IR       | 3 000–14 000                        | Absorbed at specific wavelengths by carbon dioxide, ozone, and water vapour, with two atmospheric windows |

Source: Brooks and Miller 1963; Michels 1979; WHO 1979.

<sup>a</sup>Ranges are inclusive with respect to the higher value.

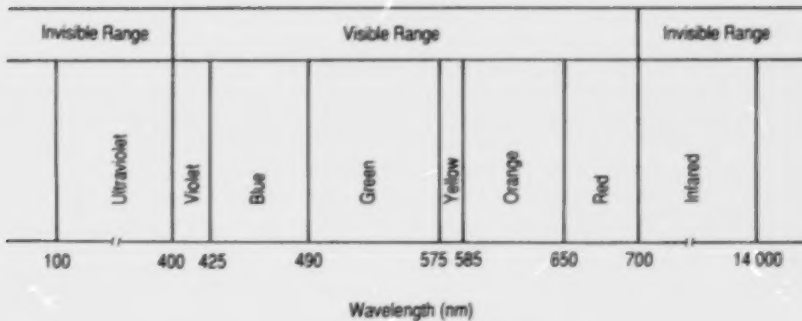
## Atmospheric interventions

Solar radiation is partially depleted and attenuated as it traverses the atmospheric layers, preventing a substantial portion of it from reaching the earth's surface. This phenomenon is due to absorption, scattering, and reflection in the upper atmosphere (stratosphere), with its thin layer of ozone, and the lower atmosphere (troposphere), within which cloud formations occur and weather conditions manifest themselves (Table 1) (Brooks and Miller 1963; McVeigh 1977; Sabins 1978; Michels 1979; WHO 1979).

The stratospheric ozone layer has a strong absorption affinity for solar UVR, depending on wavelength. Absorption, being more effective for the shorter wavelengths, tends to reach its peak at 250 nm and drops rapidly with an increase in wavelength, even beyond 350 nm. Thus, the biological harmful radiations below 280 nm (vacuum UV and UV-C) are completely shielded by the ozone layer; only a fraction of the UV-B and UV-A wavelength bands reach ground level. Depletion of the protective ozone layer beyond the critical level by certain atmospheric pollutants (fluorocarbons and nitrogen oxides) that interact photochemically with ozone will promote the transmission of highly injurious UVR (El-Hinnawi and Hashmi 1982).

The troposphere is an attenuating medium. The solar radiation is reflected and scattered primarily by clouds (moisture and ice particles), particulate matter (dust, smoke, haze, and smog), and various gases. The two major processes involved in tropospheric scattering are determined by the size of the molecules and particles and are known as selective scattering and nonselective scattering. Selective scattering is caused by smoke, fumes, haze, and gas molecules that are the same

#### A. Solar Radiation



#### B. Ultraviolet Radiation

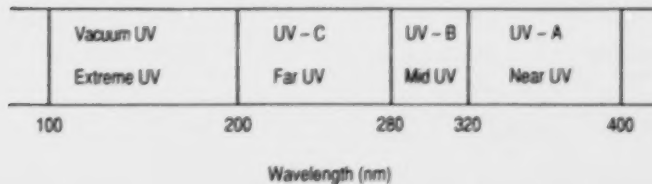


Fig. 1. Spectra of nonionizing solar radiation (A) and ultraviolet radiation (B) showing main radiation bands, their nomenclature, and approximate wavelength limits. Other synonyms: UV-A, black light; UV-B, sunburn or erythral radiation; UV-C, germicidal radiation (compiled from WHO 1979; Parmeggiani 1983; Harvey et al. 1984).

size, or smaller, than the incident radiation wavelength. Scattering in these cases is inversely proportional to wavelength and is most effective for the shortest wavelengths. The degree of scattering decreases in the following order: UV-B > UV-A > violet > blue > green > yellow > orange > red > infrared. When the atmosphere is clear and relatively transparent, selective scattering is less severe than when it is extensively polluted. Selective scattering of sunlight in the blue region of the spectrum under clear-sky conditions accounts for the blue sky when the degree of scattering is sufficiently high. This is determined by the length of the atmospheric path traversed by sunlight. With the sun overhead at noon, the sky appears white because little scattering occurs at the minimum atmospheric path length. At sunrise and sunset, however, the solar disc appears red because of the increased atmospheric path associated with blue light scattering and relatively little scattering of the red component. Selective scattering may range from 10% in the early morning to 20% in the late afternoon (McVeigh 1977).

Nonselective scattering is caused by dust, fog, and clouds with particle sizes more than 10 times the wavelength of the incident radiation. As scattering in this case is not wavelength-dependent, it is equal for all wavelengths. Because of this, clouds appear white. Clouds also reflect incident solar radiation back into space;

this varies with their thickness and albedo (ratio of reflected to incident light). Thin clouds may reflect less than 20% of the incident solar radiation, whereas a thick and dense cloud may reflect over 80%. Absorption of radiation by even thick cloud formations is less than 10%. Whereas gases, water vapour, and particulate matter cause depletion mainly in the short-wave region of the spectrum, atmospheric gases and clouds deplete absorption at specific wavelength intervals called absorption bands. These occur largely in the longer-wave region and are in contrast to the intervening regions characterized by their transmission bands, or atmospheric windows. The gases involved in the absorption phenomenon in the red and infrared regions are ozone and carbon dioxide (Table 1).

The total solar radiation received at ground level consists of direct and indirect radiation (scattered, diffused, or reflected). The UVR component does not exceed 5% of the total incident radiation at sea level under cloudless atmospheric conditions. The intensity of sunlight at ground level varies with latitude, geographic location, season, cloud coverage, atmospheric pollution, elevation above sea level, and solar altitude. The 23.5° tilt of the earth's axis affects the angle of incidence of solar radiation on the earth's surface and causes seasonal and latitudinal variations in day length. At high altitudes, the intensity of UVR is significantly higher than at sea level. The spectral distribution of solar energy at sea level is roughly 3, 44, and 53% in the UV, visible, and infrared regions, respectively. In practice, therefore, these variables need to be considered for the use of solar energy, including its UVR component.

## Transmission through different media

Solar energy impinging upon a transparent medium or target is partly reflected and partly absorbed; the remainder is transmitted. The relative values are dependent upon the optical properties of the transparent object and the solar spectrum (Dietz 1963).

Transmission of the incident solar energy through glass is a function of the type and thickness of the glass, the angle of incidence, and the specific wavelength bands of radiation. Ordinary glass of the soda-lime-silica type (window or plate glass) can transmit more than 90% of the incident radiation in the UV-A and visible regions of the spectrum, provided the  $\text{Fe}_2\text{O}_3$  content is lower than 0.035%; if it is higher, the transmittance is somewhat decreased. Increased thickness of glass diminishes transmittance. The transmittance is uniform at a high level for angles of incidence ranging from 0 to 40° and drops sharply as the angle approaches 90° (Dietz 1963). Ordinary glass is opaque to radiation in the UV-B and UV-C regions; Pyrex glass (borosilicate type) is opaque to radiation in the UV-B band and attains a maximum transmission level at 340 nm and beyond (Acra et al. 1984). The coefficient of transparency for borosilicate glass, 1.0 cm in thickness, is 0.08 at 310 nm, rises sharply to 0.65 at 330 nm, and attains a peak level of 0.95–0.99 from 360 to 500 nm (Weast 1972). The transmission properties of Pyrex are exceeded only by quartz (Dietz 1963; Kreidl and Rood 1965; Weast 1972).

Transparent plastic materials such as Lucite and Plexiglas are good transmitters in the UV and visible ranges of the spectrum (Dietz 1963). Translucent materials such as polyethylene can also transmit the germicidal components of sunlight (Fujioka and Narikawa 1982).

Solar energy passing through water is also attenuated by reflection and absorption. The proportion of transmitted sunlight in water depends on water depth; turbidity caused by organic and inorganic particles in suspension; optical properties as modified by the presence in solution of light-absorbing substances such as colouring materials, mineral salts, and humates; and wavelength of the incident radiation. Up to 10% of the solar UV-B intensity at the surface of clear seawater may penetrate to a depth of 15 m (Calkins 1974), inactivating *Escherichia coli* to a depth of 4 m (Gameson and Saxon 1967). The exponential attenuation values of UVR (200–400 nm) in distilled water are less than in seawater and range from 10/m at 200 nm to a minimum of 0.05/m at 375 nm. Values rise sharply in the visible and infrared regions of the spectrum, showing that solar UV-A has a greater penetration power in water than UV-B or visible light (Stewart and Hopfield 1965). The absorption of UVR (210–300 nm) by materials in natural water seems to be related to chemical oxygen demand (Ogura 1969). At the surface of tertiary sewage lagoons, for example, the solar UV-B intensity drops exponentially to 20% at a depth of 10 cm, 3% at 20 cm, 0.6% at 30 cm, and 0.1% at 40 cm (Moeller and Calkins 1980). Most of the UV-B absorbance in wastewater effluents is caused by the dissolved humic substances, whereas the suspended particles absorb and scatter UVR and protect bacteria during UV disinfection (Qualls et al. 1983).

Textiles used in clothing are not necessarily complete absorbers of natural UVR and may give a false sense of security against sunburn and skin cancer. The average white shirts worn by men may transmit 20% of the solar UVR, whereas lighter weaves favoured by women may allow up to 50% to penetrate to the covered skin (WHO 1979). Transmission of UVR through various samples of fabrics ranges from 64% for 100% nylon to 5% for black cotton, the values being reduced by thickness and dyes and increased with the intensity of UVR (Hutchinson and Hall 1984). The depths of penetration of UVR and visible light into the human skin are as follows: 0.01–0.1 mm for UV-B, 0.1–1.0 mm for UV-A, and 1.0–10.0 mm for the visible spectrum (Largent and Olishifski 1983).

## Artificial sources of ultraviolet radiation

Artificial sources of UVR are often used for a variety of purposes, ranging from experimenting to suntanning. Gas-discharge arcs, fluorescent lamps, and incandescent sources are some of the common artificial UVR sources, and their potential health hazards are attributable to the significant amounts of biologically effective UVR emitted (WHO 1979; Harvey et al. 1984; Pierce et al. 1986).

Photobiological research has been confined largely to laboratory work based on the use of UVR produced artificially in preference to solar radiation. The recent trend, however, is toward the use of sunlight as a supplementary source in radiation experiments.

## Relevant units

In accordance with the International System of Units, the units for the intensity of solar radiation, or any of its biologically active components, are watts per square metre ( $\text{W/m}^2$ ), or joules per square metre ( $\text{J/m}^2$ ) (WHO 1979). Wavelength ( $\lambda$ ) is expressed in nanometres ( $1 \times 10^{-9}$ ).

For photobiological research, the term UV fluence ( $F$ ) is recommended instead of UV dose (Harm 1980) and its units are watts per hour per square metre (W/h per  $m^2$ ). Fluence is quantitatively the product of radiation intensity ( $I$ ) and exposure time ( $T$ ) ( $F = IT$ ). Another photobiological unit of recent origin is the sun unit (SU), related to the erythral effect of UV-B radiation (WHO 1979).

## World distribution of solar radiation

Solar radiation is unevenly distributed throughout the world because of such variables as solar altitude, which is associated with latitude and season, and atmospheric conditions, which are determined by cloud coverage and degree of pollution. The following guidelines are useful for the broad identification of the geographic areas with favourable solar energy conditions in the Northern Hemisphere based on the collection of the direct component of sunlight. Similar conditions apply for the Southern Hemisphere (Acra et al. 1984).

The most favourable belt (15–35° N) encompasses many of the developing nations in northern Africa and southern parts of Asia. It has over 3 000 h/year of sunshine and limited cloud coverage. More than 90% of the incident solar radiation comes as direct radiation.

The moderately favourable belt (0–15° N), or equatorial belt, has high atmospheric humidity and cloudiness that tend to increase the proportion of the scattered radiation. The global solar intensity is almost uniform throughout the year as the seasonal variations are only slight. Sunshine is estimated at 2 500 h/year.

In the less favourable belt (35–45° N), the scattering of the solar radiation is significantly increased because of the higher latitudes and lower solar altitude. In addition, cloudiness and atmospheric pollution are important factors that tend to reduce sharply the solar radiation intensity. However, regions beyond 45° N have less favourable conditions for the use of direct solar radiation. This is because almost half of it is in the form of scattered radiation, which is more difficult to collect for use. This limitation, however, does not strictly apply to the potentials for solar UVR applications.

World maps illustrating the isolines of the mean global solar radiation (both direct and diffuse radiations) and solar UVR impinging on a horizontal plane at ground level are available (Landsberg 1961; Schulze 1970; WHO 1979). A set of values for average daily influx of solar UVR as a function of wavelength, latitude, and time of year have also been published (Johnson et al. 1976). The tabulated data pertain to sea level and clear-sky conditions and are distributed at intervals of latitude from 0 to 65° N and S for selected wavelengths from 285 to 340 nm. The calculated values for the erythral effect corresponding to 307 and 314 nm have been included for comparison. These data indicate that for all UVR wavelengths from 285 to 340 nm, the solar UVR flux decreases as the latitude increases. Assuming cloudless conditions, the solar UVR intensity at sea level is expected theoretically to be significantly greater at the equator than at the higher latitudes. In addition, at each latitude, the maximum intensity would be reached in summer; the minimum, in winter. A similar pattern will be followed by the erythral-response wavelengths of 307 and 314 nm. The variation with latitude or season in the calculated influx is much sharper for shorter wavelengths.

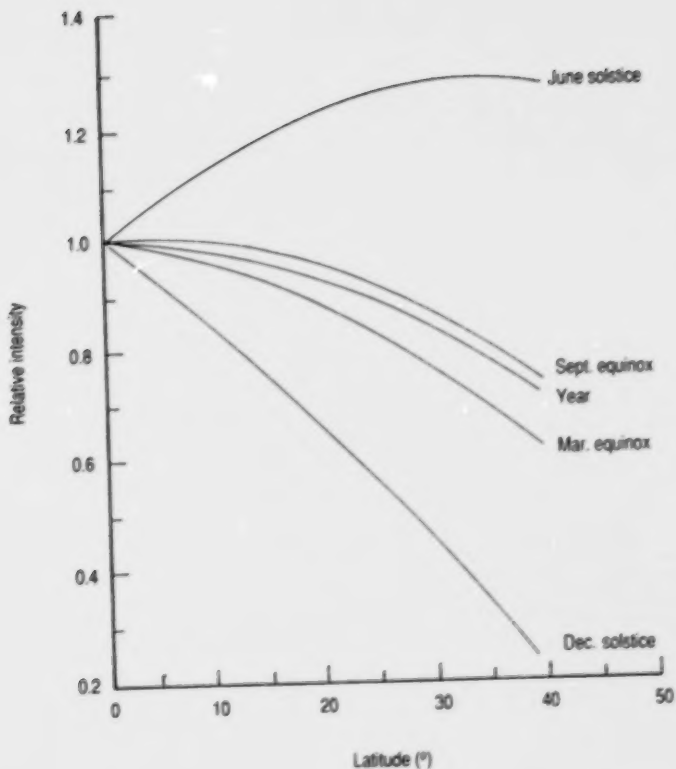


Fig. 2. Seasonal and annual variations in relative solar UV-A radiation (340 nm) for different latitudes (based on Johnson et al. 1976).

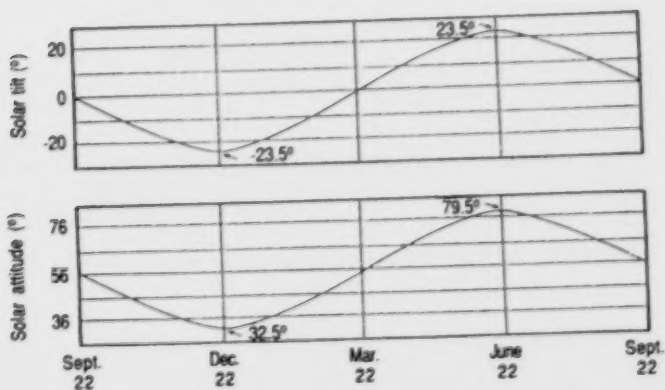


Fig. 3. Variations in angles of solar tilt and altitude worldwide (A) and for Beirut (B), as a function of time of year.

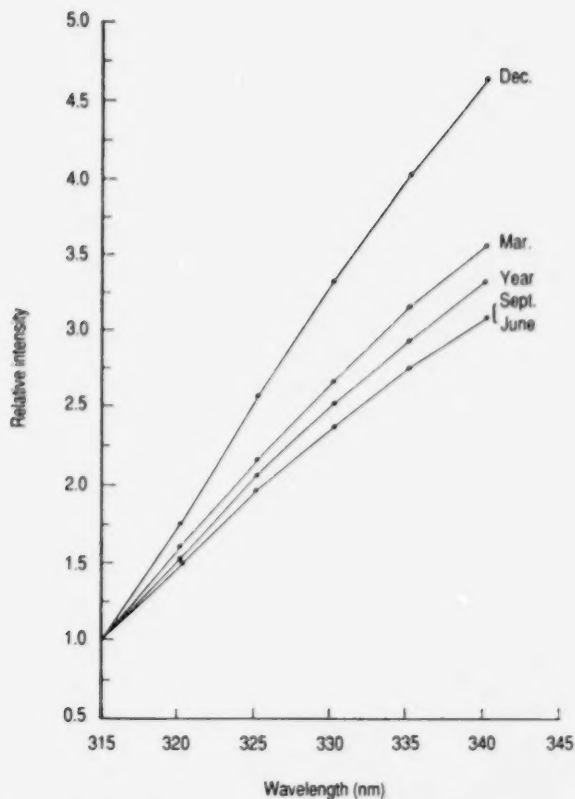


Fig. 4. Seasonal and annual variations in relative solar UV-A radiation at 35°N (based on Johnson et al. 1976).

These data (Johnson et al. 1976) were transcribed into values relative to those pertaining to the equator. Relative values (ratios) for the solar UV-A component at 340 nm as a function of latitude are shown in Fig. 2. The important inferences include the following:

- the latitudinal trends vary with season and solar angle, attaining a minimum declination in December (winter solstice) and a maximum inclination in June (summer solstice);
- the trends for the other months fall within these two limits; and
- the annual mean values show a declining trend.

These phenomena are dictated by the solar angle and its variation as a function of latitude and month (Fig. 3). Also illustrated are the seasonal variations in the angles of the earth's tilt and of the sun's altitude at noon, indicating the minimum and maximum levels attained worldwide and at 34° N in Beirut. Computations are

based on the following relationships (Michels 1979):

At equinoxes: solar altitude =  $90^\circ - \text{latitude}$

At solstices: solar altitude =  $(90^\circ - \text{latitude}) \pm 23.5^\circ$

This means that, for any latitude, the relative intensity in each month is appreciably greater for the longer UV-A wavelengths than it is for the shorter ones (Fig. 4).

Solar radiation received at ground level has been measured at meteorological stations for many years in most Western countries. This has not been the case in the developing world, where the potential and need for the development of sunlight as an alternative source of energy are even greater. For example, the few meteorological stations in Lebanon are equipped only to collect essential climatological data. Average climatic parameters of some relevance to solar radiation studies have been collected in Beirut (Fig. 5).

In 1985, after several unsuccessful attempts, we assessed the incident solar UV-A radiation at the American University in Beirut. This project monitored the maximum UV-A intensity that occurred at noon each day for 1 year, with occasional measurements of the hourly variations on randomly selected days. These data were used for the concurrent study on the solar inactivation of bacteria in drinking water and other photobiological investigations.

### Methodology

A digital radiometer (Spectroline DM-357X, Spectronics Corp., Westbury, NY, USA) was used for the solar UV-A measurements. Daily readings at noon for 4 or 5 consecutive days each week were taken. A total of 244 readings were recorded from 4 February 1985 to 26 February 1986. Advancement of the local time from 1 May to 15 October 1985 affected the collected data to some extent.

Three readings were taken within 2 min on each occasion; their average was recorded. In each case, the radiometer sensor or probe was placed horizontally for horizontal readings (*H*), and vertically facing south for vertical readings (*V*). The corresponding vertical–horizontal ratios (*V/H*) were also calculated and recorded. The average weekly and monthly values for each of the three parameters were computed from the accumulated data. Weekly averages were used in plotting graphs for each set of data. Moving averages were used to smooth random variations in the plotted data (Berthouex and Hunter 1981).

### Results

For incident solar UV-A radiation on a horizontal surface, the maximum monthly average occurred in June ( $1820 \mu\text{W}/\text{cm}^2$ ), and the minimum level occurred in December ( $479 \mu\text{W}/\text{cm}^2$ ) (see Appendix 1). In the south-facing vertical

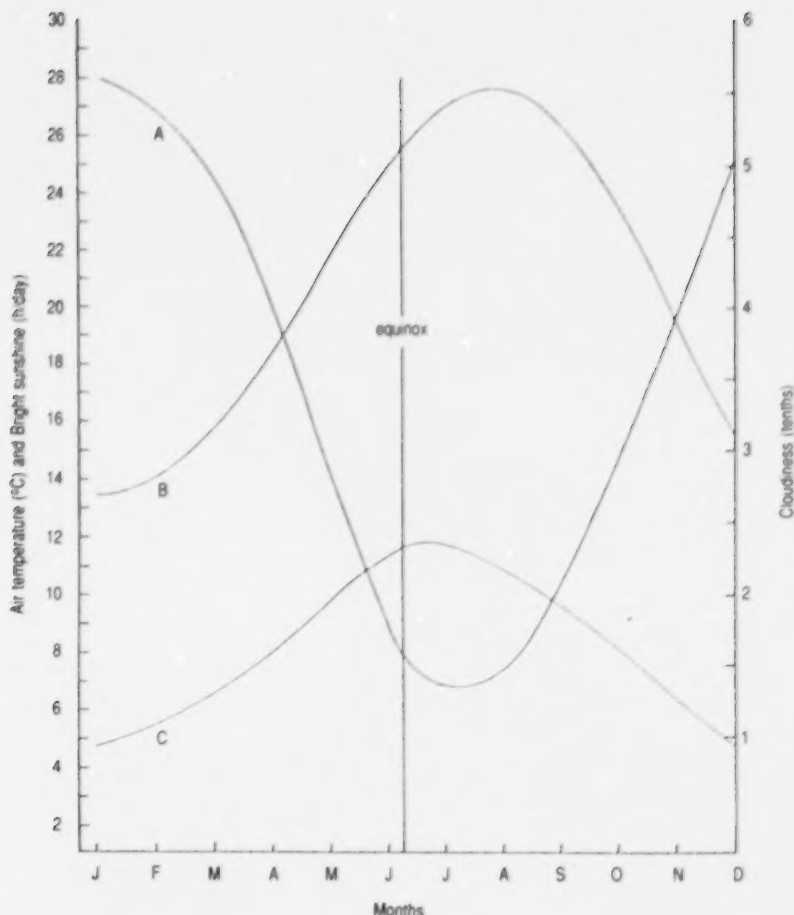


Fig. 5. Monthly mean values of (A) cloudiness, (B) air temperature, and (C) bright sunshine for Beirut from 1876 to 1957 (computed from Gingerich 1958).

position, the minimum value of  $275 \mu\text{W}/\text{cm}^2$  was attained in June and the peak level of  $705 \mu\text{W}/\text{cm}^2$  occurred in February 1986.  $V/H$  ratios, like the radiation values for the horizontal position, reached a minimum of 0.15 in June and a maximum of 1.05 in December.

Solar UV-A intensity varies because of changes in the earth's angle of tilt (see Appendix 2). Peak seasonal values are attained in summer ( $1525 \mu\text{W}/\text{cm}^2$ ) for the horizontal position and in winter for the vertical position ( $627 \mu\text{W}/\text{cm}^2$ ) and  $V/H$  ratio ( $0.870 \mu\text{W}/\text{cm}^2$ ). The annual mean values in each of these three cases occurred between summer and autumn.

Figures 6-8 reflect the weekly random variations caused by alterations in the incident solar UV-A radiation, but the sinusoidal curves based on the moving

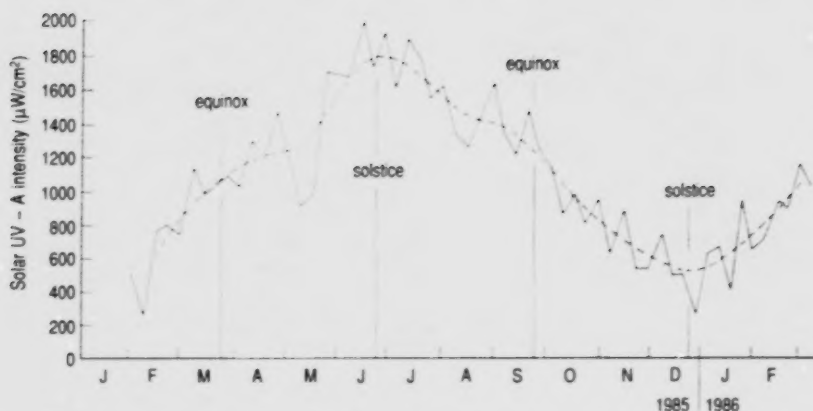


Fig. 6. Mean weekly values (solid line) and moving averages (broken line) for solar UV-A radiation intensity on a horizontal surface in Beirut from 28 January 1985 to 26 February 1986.

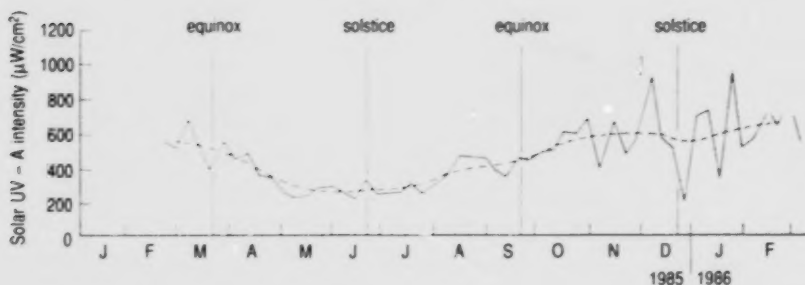


Fig. 7. Mean weekly values (solid line) and moving averages (broken line) for solar UV-A radiation intensity on a vertical surface in Beirut from 28 January 1985 to 26 February 1986.

averages are obviously smoother. The salient features are that their maximum and minimum levels almost coincide with the respective summer and winter solstices in the Northern Hemisphere and that their symmetrical pattern is partitioned by the summer (June) solstice.

For the horizontal surface (Fig. 6), the intensity reaches a peak level of some  $1\,800\,\mu\text{W}/\text{cm}^2$  in June and decreases to its lowest level close to  $500\,\mu\text{W}/\text{cm}^2$  in December. The difference between these two levels ( $1\,300\,\mu\text{W}/\text{cm}^2$ ) is appreciable and important. The higher range of values in excess of the annual mean of about  $1\,100\,\mu\text{W}/\text{cm}^2$  (Appendix 2) prevails from the spring equinox (22 March) to the autumn equinox (22 September). The lower range of values, falling below the annual mean, prevails in the remaining months of the year. Thus, the equinoxes form the demarcation points at which the solar altitude is at its midpoint, which corresponds to  $56^\circ$  in Beirut (Fig. 3). Alterations in the observed intensities may occur with time (i.e., hourly and seasonal variations) because these observations apply to the midday intensities under varied climatological conditions.

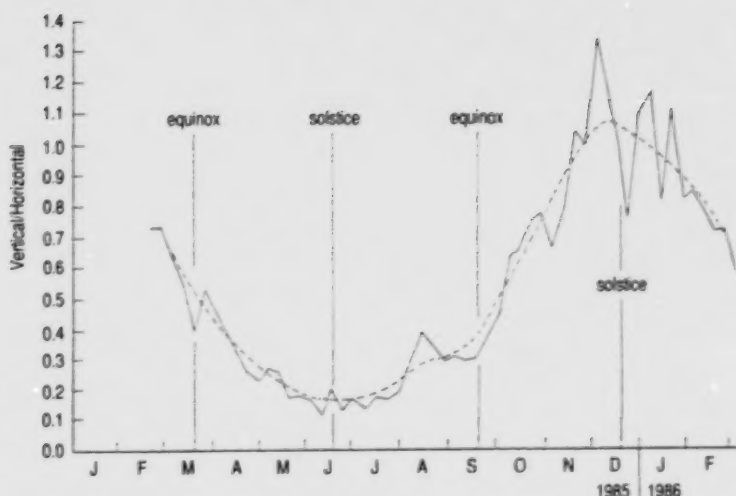


Fig. 8. Mean weekly values (solid line) and moving averages (broken line) for the vertical/horizontal ratio for solar UV-A radiation intensity in Beirut from 28 January 1985 to 26 February 1986.

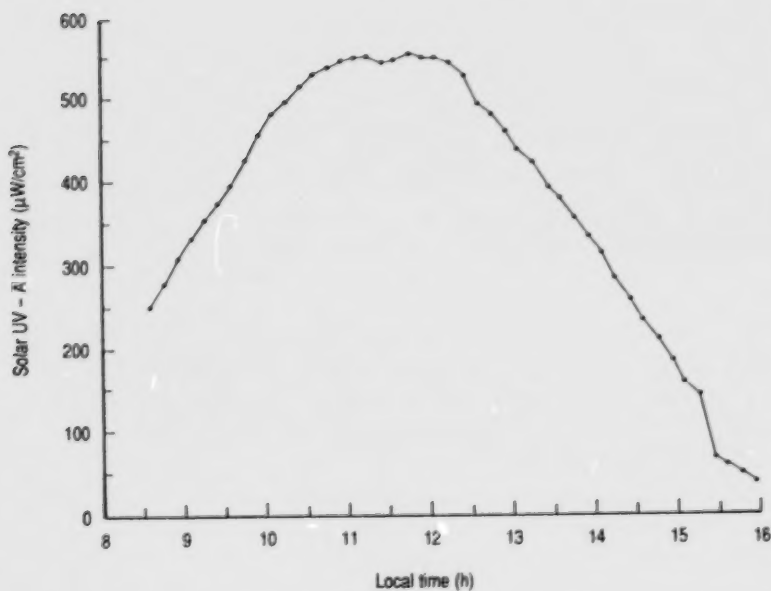


Fig. 9. Distribution of mean values for solar UV-A intensity on a horizontal surface as a function of time of day under clear-sky conditions in Beirut (7-9 October 1985) (data from Appendix 3).

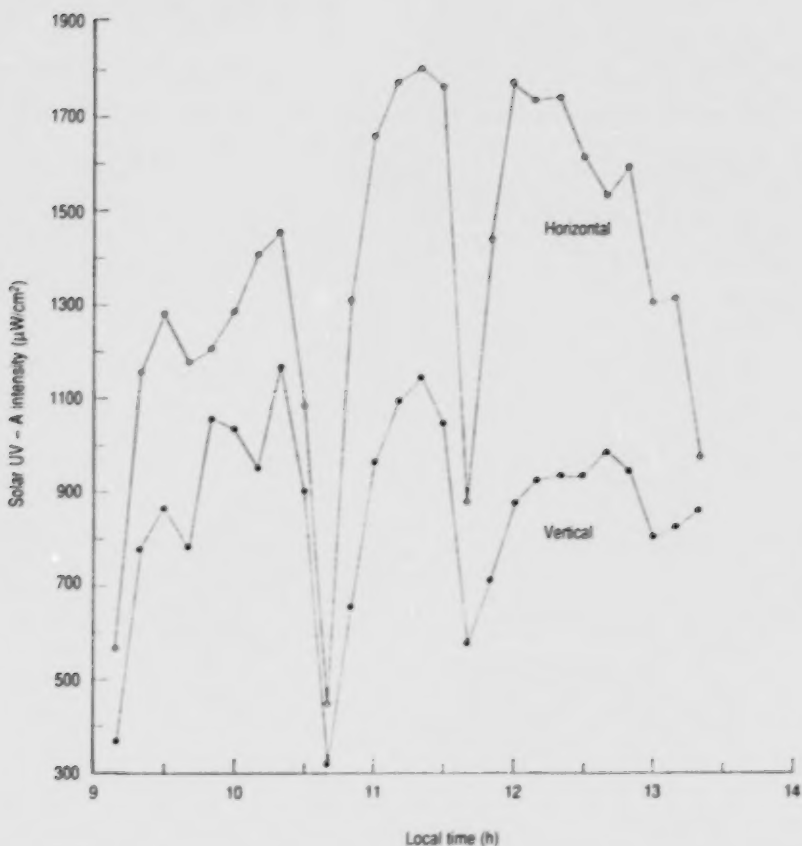


Fig. 10. Effect of target orientation on the received solar UV-A radiation throughout the day under cloudy conditions in Beirut (3 April 1985).

The annual mean value of  $480 \mu\text{W}/\text{cm}^2$  (Appendix 2) for the vertical surface closely coincides with intermediate values yielded at the two equinoxes (Fig. 7). The monthly mean intensity levels greater than the annual mean form a plateau in autumn and winter with a slight dip at the winter solstice. For  $V/H$  ratios (Fig. 8), the annual mean value of 0.56 is almost equal to the ratios attained at the two equinoxes, but lower values occur in spring and summer, whereas higher ones are produced in autumn and winter.

Solar UV-A intensity on a horizontal target, as measured on 3 consecutive days (7–9 October 1985) under clear-sky conditions, varied from  $500 \mu\text{W}/\text{cm}^2$  at 0835 to a peak value of  $1105 \mu\text{W}/\text{cm}^2$  at 1145. It then receded to a low of  $70 \mu\text{W}/\text{cm}^2$  at 1555 (Fig. 9; see Appendix 3).

Heavy, transient clouds lowered the received intensity on both the horizontal and vertical targets (Fig. 10). Under hazy conditions, the UV-A intensity levels for the vertical target were greatly suppressed between 0900 and 1400 (Fig. 11; see

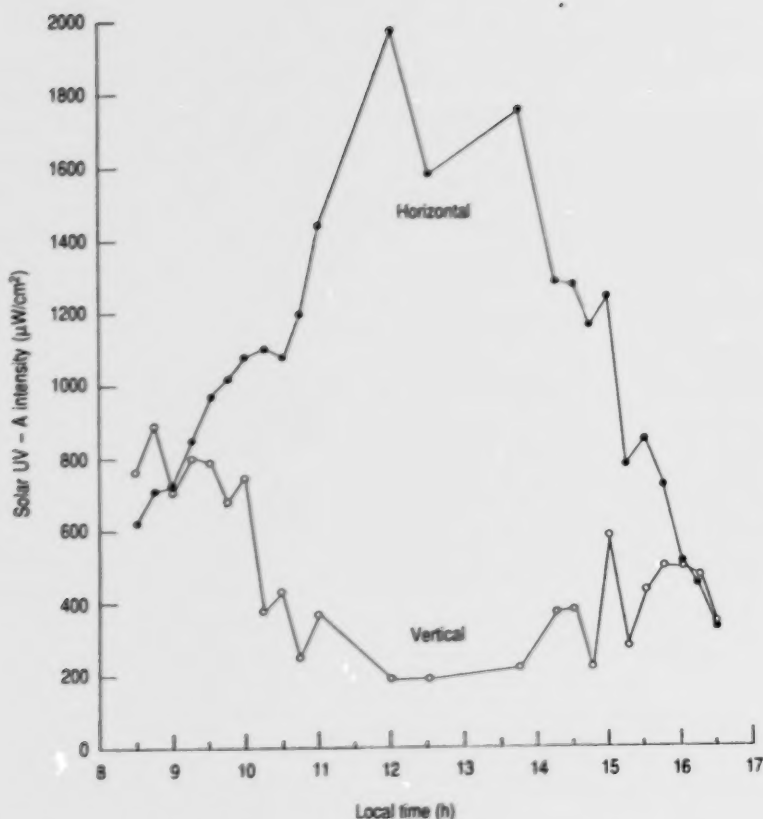


Fig. 11. Effect of target orientation on the received solar UV-A radiation throughout the day under hazy-sky conditions in Beirut (2 June 1985) (data from Appendix 4).

Appendix 4). This could be due to the combined effects of the high solar altitude in June (see Fig. 3), increased humidity, and light scattering by atmospheric particles.

Higher radiation intensities prevailed throughout the day when the sky was clear. However, the mean percentage for the proportion of UV-A intensity on an overcast day was 5.2% compared with 4.4% for clear-sky conditions (see Appendix 5). This difference may be attributed to the diminished sunlight intensity associated with radiation absorption by cloud formations, which is more effective in longer wavelengths.

With the target inclined at 35° (equivalent to Beirut's latitude), under clear-sky conditions, the incident UV-A intensity surpassed those for the horizontal and vertical positions throughout the day (Fig. 12). The differences in intensity induced by target orientation are appreciably diminished in the early morning and late afternoon (Fig. 13).

For the inclined target at any time of the day, the UV-A intensity prevailing in

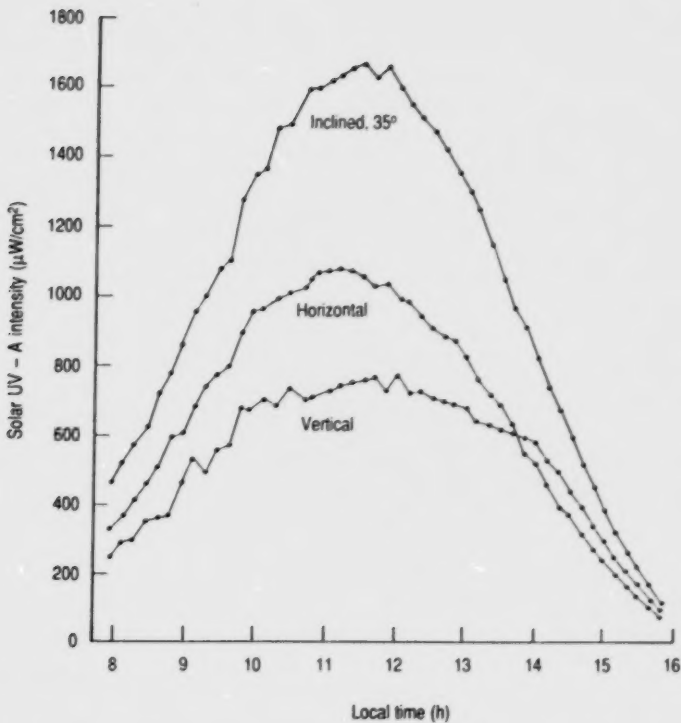


Fig. 12. Effect of target orientation on the received solar UV-A radiation throughout the day in Beirut (23 October 1985).

May–June was appreciably higher than in September–October (Fig. 14). The linear regression equations observed from 1000 to 1300, at 34° N, can be used to calculate values for intensity at a given time or when a given intensity will be attained. At noon in Beirut, for instance, the UV-A intensity under average conditions should be about 19 W/m<sup>2</sup> (1 900 μW/cm<sup>2</sup>) in May–June, and about 17 W/m<sup>2</sup> (1 700 μW/cm<sup>2</sup>) in September–October on an inclined target.

## Discussion and conclusions

Lebanon is among the Middle-Eastern countries that have yet to appreciably exploit the abundant sunlight as a natural source of renewable energy. Reliable data on solar radiation and its components are needed for a great variety of purposes. The variations in topography and microclimates call for data collection in representative localities on a long-term basis. The data reported herein are applicable to Beirut or any other locality with similar conditions, latitude, and elevation.

The proportion of solar UVR that reaches the ground by escaping atmospheric attenuation amounts to about 4% (Brooks and Miller 1963), depending on

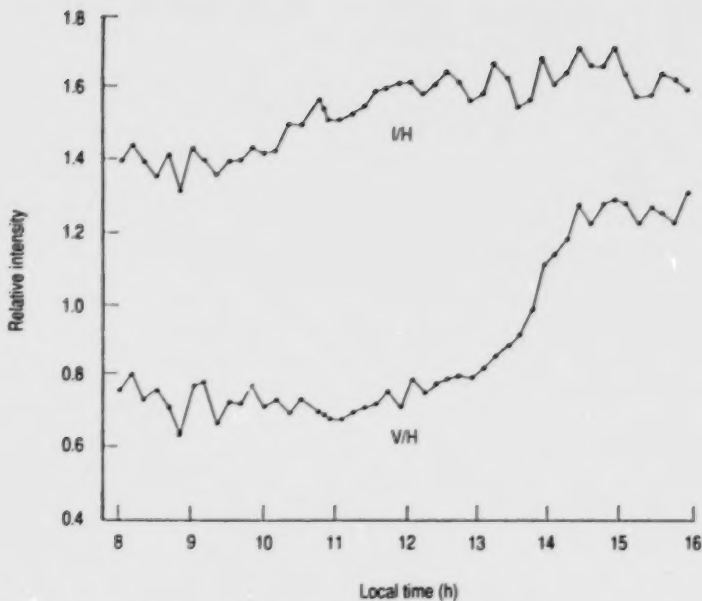


Fig. 13. Hourly trends in the ratios for solar UV-A intensity for different target orientations (inclined/horizontal, I/H; vertical/horizontal, V/H) throughout the day in Beirut (23 October 1986).

wavelength and latitude. This attenuation is more effective for shorter UVR wavelengths, i.e., the proportion of UV-A (340 nm) to UV-B (300 nm) at 35° N should be 100:1, with a yearly mean of 165:1 (Johnson et al. 1976). The UV-A radiation constitutes about 5% of the global radiation received in Beirut (see Appendix 5). Ground level UV-A radiation at any latitude seems to exceed UV-B radiation, thus compensating for its weaker photobiological effects. In addition, the superior penetration power of UV-A through transparent or translucent media such as glass, plastics, and water is of practical importance (Dietz 1963; Kreidl and Rood 1965; Weast 1972).

The study demonstrated an annual mean value of approximately  $1\ 100\ \mu\text{W}/\text{cm}^2$  for the UV-A intensity incident on a horizontal target and  $480\ \mu\text{W}/\text{cm}^2$  for a south-facing, vertical target (see Appendix 2). Marked deviations from these intensity levels are largely induced by the seasonal alteration in the earth's angle of tilt and, hence, in solar altitude and atmospheric path length.

At the winter and summer solstices (22 December and 22 June), solar altitudes (solar angles) at noon in Beirut would be 32.5° and 79.5°, respectively (see Fig. 3). The atmospheric path length to be traversed by the incoming UV-A radiation is inversely proportional to these angles. This, in turn, influences the magnitude of atmospheric attenuation. The maximum solar altitude attained at the summer solstice explains the establishment of the summit level in the solar UV-A radiation received on a horizontal target. The inverse situation is manifested at the winter solstice (see Fig. 3). For instance, it was observed that the daily solar UV-B in

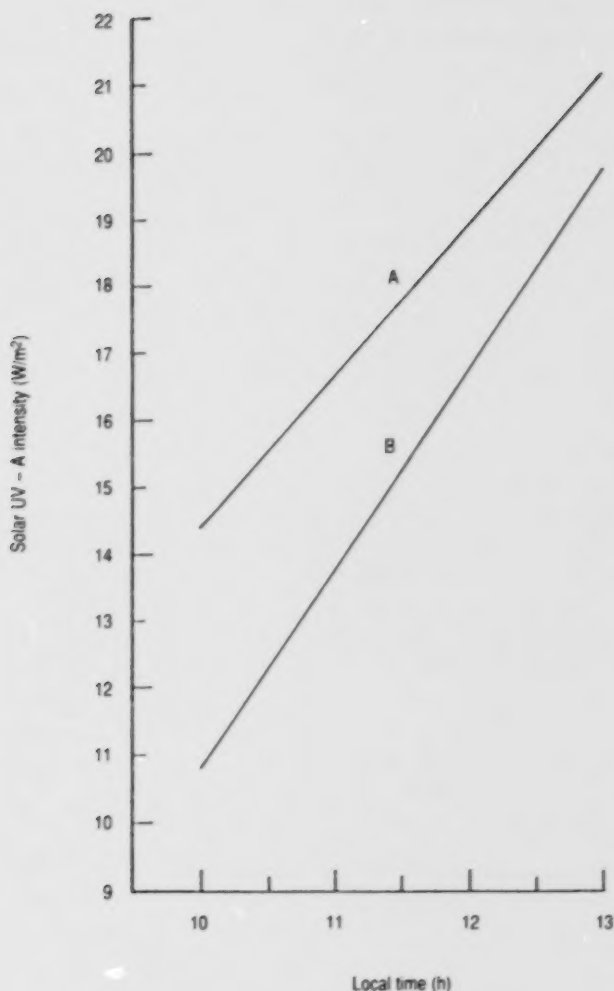


Fig. 14. Linear regression plots for the mean solar UV-A radiation received on a 35°-inclined target throughout the day for May-June (A) and September-October (B) in Beirut (1986). (A)  $I = 2.25T - 8.12$ ; (B)  $I = 2.99T - 19.09$ ;  $I$ , solar UV-A radiation intensity ( $\text{W/m}^2$ );  $T$ , local time (h).

Riyadh, Saudi Arabia (24.4° N), decreased from September to December by about 40% (Hannan et al. 1984).

The target orientation played an important role with respect to the intensity of the incident radiation (Figs 10-12). As a rule of thumb, the smaller the angle of incidence at the surface of the target, the greater the measured radiation intensity, and vice versa (Michels 1979). This explains partially the annual radiation pattern illustrated in Fig. 7 for the UV-A radiation on a vertical target, which contrasts the pattern on a horizontal target (Fig. 6). For maximum radiation influx, the target

should face the sun continuously ("sun tracking") and be inclined at an angle equivalent to the latitude (to minimize the angle of incidence) (Figs 11 and 12).

The apparent motion of the sun from sunrise to sunset imposes a profound effect on the quantity of solar radiation intercepted by a surface. The received radiation per unit area increases with the time of day to reach a peak level at noon; it then tapers off as sunset approaches (Figs 9, 11, and 12). The magnitude of the variable radiation intercepted is a function of time of day and time of year for any given latitude (McVeigh 1977; Michels 1979).

Day length, a function of latitude and time of year, is important in estimating daily and annual radiation (Michels 1979). Values for Beirut range from 9.78 h in December to 14.53 h in June, with a mean of 12.14 h. The monthly mean hours of bright sunshine per day observed in Beirut from 1876 to 1957 (Fig. 5) attained a peak in June and a minimum in December. In conclusion, May to September is a particularly important period for solar radiation exposure in Beirut, characterized by longer daylight and bright sunshine hours, increased solar radiation, and diminished cloudiness.

Many people in most developing countries suffer from the inadequacy or hazardous condition of public water supplies (WHO 1985). A wide variety of known waterborne diseases, including those associated with children's diarrhea, are rampant (Tartakow and Vorperian 1980; Feachem et al. 1983; WHO 1984, 1987). This prompted the establishment of the International Drinking Water Supply and Sanitation Decade. It aims at providing about 90% of the human population with an adequate, safe community water supply by 1990 (WHO 1985).

In Lebanon, the shortage of community water supplies, their actual or potential pollution from anthropogenic sources, inadequate treatment, and the resultant spread of associated diseases are still unresolved problems (Acra et al. 1985). To curb these issues would require implementing feasible measures for prevention and treatment. These should include sanitation and disinfection of drinking water.

### **Physical methods**

Formation of mutagenic and carcinogenic agents in water and wastewater effluent treated with chlorine has prompted research to seek alternative disinfecting methods that would minimize environmental and public health impacts. The technology, based on nonchemical methods, is undergoing rapid development. Some techniques are already available commercially. This category is represented by techniques employing such physical principles for disinfection as UV radiation, ultrasound, ultrafiltration, reverse osmosis, heating, freezing, and ionizing radiation (Cheremissinoff et al. 1981). Disinfecting small quantities of water by pasteurizing with heat or solar energy is a technology with some potential, but requires further development (Cheremissinoff et al. 1981; Ciochetti and Metcalf 1984). The recently developed method for water disinfection by direct exposure to solar radiation (Acra et al. 1980, 1984) is further described in the following sections.

### **Chemical methods**

Chemical methods depend mostly on selected chemicals with oxidizing and biocidal properties. Their practical applications range from removing undesirable constituents to disinfecting water supplies, wastewater treatment effluent, or industrial waters. The most commonly used chemicals include ozone, chlorine and some of its compounds, potassium permanganate, and hydrogen peroxide.

Ozone has been used for water disinfection for about 80 years in France, Germany, and other European countries. It is now undergoing a critical evaluation

as a possible alternative to chlorine when used alone or in conjunction with other disinfection systems (Foster et al. 1980; Kott et al. 1980; Dolora et al. 1981; Venosa 1983; Rakness et al. 1984; Wickramanayake et al. 1984; Den-Blanken 1985). There is some evidence that it forms smaller amounts of hazardous trihalomethanes (THM) when employed to treat polluted waters or wastewater effluent than either chlorine or chlorine dioxide. However, its potential for producing other equally toxic substances is still not clearly defined (Glaze 1987). Ozonation has become popular in North America partly because of its superiority over chlorination. It enhances the coagulation process despite its inherent weakness in leaving practically no residual in the distribution system.

Interhalogen compounds, formed from two different halogens, resemble their parent substances in properties and germicidal characteristics. The interhalogens BrCl, ICl, and IBr have recently been investigated as possible alternative disinfectants for water and wastewater effluent (Groninger and Mills 1980; Cheremissinoff et al. 1981). Added to water, they rapidly hydrolyze to the corresponding hypohalous acids, which are stronger oxidants and disinfectants than hypochlorous acid. For instance, BrCl is hydrolyzed to HCl and HOBr. However, their improved germicidal activity is counterbalanced by the formation of haloforms. They react with humates in water or wastewater effluent by the haloform reaction (HOBr, for example, reacts with humates yielding bromoform). In this context, hypobromite would be formed in seawater by reaction of the natural bromides with hypochlorites in chlorinated wastewater effluent or cooling waters from power plants (Sugam and Helz 1980; Wong 1982; Bousher et al. 1986). This also applies to natural waters rich in bromides with subsequent formation of bromoform and other trihalomethanes (Amy et al. 1984; Rav-Acha, Choshen et al. 1985; Rav-Acha, Serri et al. 1985; Ishikawa et al. 1986; Guttman-Bass et al. 1987). Consequently, coastal groundwater affected by seawater infiltration should create some concern if used for drinking.

Using hydrogen peroxide for water disinfection began in the 1950s in Eastern Europe (Laubusch 1971). Although it has been well known for its high oxidative and germicidal activity, its application as a water disinfectant has not gained wide acceptance. Its increasing use, however, has been noted (Gaudy and Gaudy 1980). The degradation of organic matter in water treated sequentially with up to 0.5% by weight of hydrogen peroxide and UV radiation (>200 nm) has been reported (Malaiyandi et al. 1982). In another form of application, hydrogen peroxide produced no significant oxidation of soluble manganese in water containing organic matter in the pH range of 5.0–8.0 (Knocke et al. 1987). A newly marketed product (Sanosil, Sanosil AG, Feldmeilen, Switzerland) is claimed to be applicable to large-scale water disinfection; its effective bacteriostatic and fungicidal activity has been demonstrated at concentrations of 10–35 mg/L on *Escherichia coli*, *Klebsiella pneumoniae*, *Streptococcus aureus*, *Pseudomonas aeruginosa*, *Proteus mirabilis*, *Micobacter* spp., *Clamidia sporogenes*, and *Candida albicans*. The two active biocidal constituents of this product are hydrogen peroxide and colloidal silver.

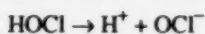
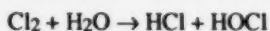
## Chlorination and dechlorination

The use of chlorine and some of its derivatives will continue as an integral part of the disinfection process in water and wastewater treatment. This also applies to

developing countries, where this mode of disinfection is fairly well established (Mara 1978; Droste and McJunkin 1982; Smethurst 1983). Apart from almost a century of chlorination practices (Laubusch 1962a, b; Cheremissinoff et al. 1981), two other favourable determinants are the technical expertise already acquired and the relatively low costs involved. In the wake of the recent discovery of the formation of THM in chlorinated natural waters (Rook 1974), and their potential health hazards (Glaze et al. 1980; Williamson 1981; Carpenter and Beresford 1986), its credibility is diminishing.

Alternative disinfecting agents such as chlorine dioxide (Rav-Acha et al. 1985b), UV light (Severin et al. 1984; Scheible 1987), and UV light in conjunction with hydrogen peroxide (Crandall 1986) are being considered. However, the formation of mutagens and carcinogens in chlorinated waters and wastewaters can be abolished or minimized by modifying the unit processes (Stelter et al. 1984; Fiessinger et al. 1985; Finger et al. 1985; Huang et al. 1985; Kool et al. 1985; Moyers and Wu 1985; Suh and Abdel-Rahman 1985; Means et al. 1986; Rogers and Lauer 1986; Guttman-Bass et al. 1987; Knocke et al. 1987). The potential health impacts that are yet to be clearly discerned and the toxicity to aquatic life resulting from discharged chlorinated effluent (Brungs 1973; Jolley et al. 1980) do not seem to outweigh the public health benefits derived from chlorination practices (Cortruvo 1985). However, as the controversy continues, epidemiological studies (Craun 1985) and the pertinent drinking water standards and legislation (Toft 1985) are being revised.

Reactions of chlorine in water that form the basis for its application as a disinfectant and oxidant are as follows:



These reactions in water devoid of other inorganic or organic matter that could react with chlorine are pH and temperature dependent. The products, hypochlorous acid (HOCl) and hypochlorite ions ( $\text{OCl}^-$ ), are referred to as free available chlorine (FAC). The biocidal activity is attributed chiefly to HOCl, as it is more effective than the  $\text{OCl}^-$ . In the presence of natural or added ammonium ions, HOCl reacts to form chloramines, known as combined available chlorine (CAC). As a disinfectant, FAC is more effective. It is essential to chlorinate beyond the subsequent attainment of FAC at the desired level for optimal biocidal effectiveness ("free residual" chlorination).

The influencing factors to be considered in chlorination practices are the following:

- chlorine concentration,
- contact time,
- pH,
- temperature, and
- interfering substances.

The relationship between chlorine concentration ( $C$ , milligrams per litre) and contact time ( $T$ , minutes) required for a specific percentage destruction of

microorganisms is expressed as a constant ( $CT = K$ ) (Gaudy and Gaudy 1980). The proper use of this  $CT$  relationship to determine adequate water chlorination requirements has been emphasized as an approach to prevent and control waterborne diseases. Minimum  $CT$  values of 15–30 for systems using groundwater as a source and 100–150 for those using surface supplies have been recommended (Lippy 1986). Based on these values, the required FAC concentration can be determined mathematically for a given contact time. Once the chlorine demand ( $D$ ) for a water supply is determined by testing, then the optimal chlorine dose to attain the desired free chlorine residual ( $C$ ) can be calculated by addition: chlorine dose =  $D + C$ .

One of the factors in the many waterborne disease outbreaks in the United States in the past decades was failure to comply with the  $CT$  relationship in chlorination practices (Lippy and Waltrip 1984; Bitton et al. 1986; Lippy 1986; Williams and Akin 1986). In addition, the need for the disinfection of wastewater discharged into streams has been emphasized and justified by the 23 different kinds of pathogenic organisms present in wastewater from US communities (Shertzer 1986).

Excess chlorine residuals can be controlled by a dechlorination procedure. Of the various chemicals used for the partial or complete removal of the residual chlorine in water or wastewater, sulfur dioxide gas ( $SO_2$ ) is the most common (Laubusch 1971; Cheremissinoff et al. 1981; Finger et al. 1985; Huang et al. 1985). Dechlorination is often applied to heavily dosed water supplies as they are aesthetically objectionable to consumers or undesirable for industrial water uses. Chlorinated cooling waters and wastewaters need to be dechlorinated before discharging into water bodies in view of their toxicity to aquatic life. They have also potentially harmful effects because of the formed THM.

## Household methods

There are many situations where individuals or families would need to resort to simple and effective methods for drinking-water disinfection. These include the following:

- catastrophic conditions leading to displacement (earthquakes, floods, hurricanes, wars, or civil disturbances);
- emergencies arising from flourishing waterborne diseases; and
- resident populations and foreigners at risk in endemic areas with unsafe water supplies.

Physical methods (boiling or the use of ceramic filters), chemical methods (chlorine compounds in solution or tablet form, e.g., sodium hypochlorite solutions, calcium hypochlorite tablets, organic chlorine compounds, iodine solution, and organic iodine compounds) and others have been recommended for such cases (Morris et al. 1953; Gershenfeld 1957; Hadfield 1957; Cox 1969; O'Connor and Cooper 1970; WHO 1972, 1973; Rajagopalan and Shiffman 1974; UNHCR 1982).

None of these methods is entirely free from practical problems that could induce users to revert to untreated water. Fuelwood, for instance, for boiling is no longer a tenable practice, particularly in areas where it is absent or being depleted. Besides, the flat taste of boiled water discourages some consumers. The diverse types of

ceramic filters have a wide range of pore sizes and present difficulties in selection. They suffer frequent clogging of the ceramic candles and often leak through disguised fine cracks. Proprietary halogen preparations frequently lead to consumer complaints and rejection because of the undesirable tastes and odours imparted to the water. It is especially so if high doses are applied inadvertently or as required in cases of heavily polluted waters. Relief agencies are often trapped in a dilemma by the requirements for importing and distributing, in addition to shortages, cost acceptability, and expiry dates. These issues encourage attempts to resolve them through the development of practical and effective techniques, simple enough to be applied by individuals or households.

## Photoinactivation

The concept of photodynamic inactivation (PDI) of microorganisms evolved from experiments made in the early 19th century. It was firmly established, however, after the discovery of the inactivation of *Paramecium* spp. by visible light in the presence of an exogenous photosensitizing dye (acridine) (Raab 1900). Two types of photosensitizing compounds are known (Harrison 1967; Chamberlin and Mitchell 1978; Senger 1980):

- exogenous: fluorescent substances or dyes such as eosin, methylene blue, and benzopyrene; and
- endogenous: porphyrins, cytochromes, cytochrome oxidase, aromatic amino acids, flavins, tryptophan, and chlorophylls.

Several microorganisms and aquatic ecosystems have shown sensitivity to solar UVR, including viruses, algae, and fungi (Perdrau and Todd 1933; Hiatt et al. 1960; Crowther and Melnick 1961; Jagger 1967, 1981; Billen and Green 1975; Berry and Noton 1976; Propst and Lubin 1978; Acher and Elgavish 1980; Calkins and Thordardottir 1980; Kapuscinski and Mitchell 1981; Worrest et al. 1981; Jabara 1984; Wei et al. 1985). The rapid destruction of saprophytic strains of *Mycoplasma* by artificial visible light in the presence of toluidine blue and air has been reported (Cooney and Krinsky 1972). Coliforms in water and sewage have been completely inactivated by exposure to sunlight for about 1 h in the presence of methylene blue or rose bengal; the added dye is removed by absorption on bentonite (Acher and Juven 1977). A new technique for the photodynamic disinfection of municipal and industrial wastewaters, which also results in the photodegradation of pesticides and anionic surfactants therein, has been suggested. The technique is based on the use of exogenous dye sensitizers, aeration, and sunlight, with the possibility of reusing the treated effluent for crop irrigation (Acher 1985).

## Aquatic photochemistry

Photochemical reactions induced by natural or artificial light have been known for some time, but much of this field remains obscure. Of particular interest is the photochemistry of the hydrosphere, which is continuously experiencing light-induced chemical reactions in the surface layer (photic zone). Inorganic and organic chemical pollutants in natural surface waters capable of absorbing solar energy with consequent chemical changes, referred to as photoreactive

chromophores, can lead to direct photolysis reactions. Some of the better known chromophores include inorganic substances such as nitrites, nitrates, iodates, hydrogen peroxide, and ferrous compounds (Zafiriou et al. 1984).

The fate of disinfectants added to wastewater effluent and cooling waters used in industries that are discharged to surface waters is of importance in aquatic biology. Sunlight plays a prime role in their photodecomposition, as was demonstrated with experiments in which hypochlorite and hypobromite (formed by interaction of chlorine and natural bromides in seawater) were found to be photosensitive, the latter being easier to decompose (Wong 1982). In addition, volatilization into the atmosphere has been proposed as a possible pathway for the dissipation of the haloforms formed in water, with subsequent enhanced dilution and further photochemical degradation (Groninger and Mills 1980). Decay and dissipation models for chlorine residuals in natural waters have been developed. These models predict that the nocturnal discharge of chlorinated effluent would have a much greater impact on aquatic life, given the absence of light-induced decomposition (Lin et al. 1983; Yamamoto et al. 1985).

The photochemical reactions of the hypohalites formed in aqueous solutions of chlorine, bromine, and iodine are somewhat similar, except for the absorption spectra and reaction rates (Allmand et al. 1927; Allmand and Webb 1928; Farkas and Klein 1948). Their photodecomposition is wavelength-dependent, with increased decay rates in the shorter wavebands within the spectral region of 200–440 nm and the possible liberation of the highly reactive singlet oxygen, as has been noted for the surface of fresh and coastal waters (Zafiriou et al. 1984). It can be postulated, then, that aqueous halogen solutions are subject to photodecomposition by the effective radiation in the UV-B, UV-A, and blue light bands of the solar spectrum, and that these reactions could be of practical importance.

The germicidal action of sunlight has long been recognized (Downes and Blunt 1877), but the ecological implications and the potentials for practical applications have to be researched more thoroughly. Studies undertaken by the authors since 1979 at the American University of Beirut were aimed at solar disinfection of drinking water and oral rehydration solutions based on a batch system using clear or blue-tinted containers made of glass or plastic (Acra et al. 1980; Acra et al. 1984). The results confirm the effectiveness and feasibility of the solar decontamination of water in small quantities ( $\leq 3$  L). Therefore, the possibility of applying the same fundamental principles to a continuous-flow system was investigated. Accordingly, simple prototype units were designed, and their effectiveness in decontaminating water by exposure to sunlight was assessed.

### Inactivation kinetics

In a continuous-flow system operated under uniform flow and solar UV-A intensity at all points inside the transparent reactor, inactivation of the test bacteria as a function of intensity is assumed to comply with first-order kinetics (Severin et al. 1984; White et al. 1986; Scheible 1987). This exponential relationship, which is not always observed over the entire period of treatment (Gaudy and Gaudy 1980), can be approximated by the following equation:

$$N/N_0 = e^{-KIT} \quad [1]$$

where  $N$  is bacterial density after exposure (colony-forming units (CFU) per millilitre of effluent),  $N_0$  is initial bacterial density (CFU per millilitre of influent),  $N/N_0$  is the bacterial survival ratio,  $K$  is the inactivation rate constant (square centimetres per microwatt minute,  $\text{cm}^2/\mu\text{W min}$ ),  $I$  is the intensity of received solar UV-A radiation (microwatts per square centimetre),  $T$  is time of exposure to solar UV-A radiation (min), and  $e$  is equal to 2.7182.

Units for  $I$ ,  $T$ , and  $K$  may be substituted with watts per square metre, hours, and square metres per watt hour ( $\text{m}^2/\text{W h}$ ), respectively. The dimensionless value of the constant is a direct measure of bacterial sensitivity to solar UV-A radiation. The experimental  $K$  value for each test organism can be computed from equation 1 and is represented by the slope of the corresponding survival curve.

Exposure time ( $T$ ) corresponds to the residence time of the water as it flows through from the inlet to the outlet port of the reactor. Its value can be calculated from the following expression:

$$T = Q/V \quad [2]$$

where  $T$  is time of exposure to solar UV-A radiation (minutes),  $Q$  is total capacity of the transparent part of reactor (litres), and  $V$  is the flow rate of water passing through the reactor (litres per minute).

If the bacterial survival ratio ( $N/N_0$ ) is to be expressed in terms of percentage, then equation 1 changes:

$$S = (100) e^{-K/IT} \quad [3]$$

where  $S$  is bacterial survival (percent). Other symbols and units are the same as for equation 1.

Fluence ( $F$ ), or radiation dose, is the product of solar UV-A intensity ( $I$ ) and exposure time ( $T$ ).

$$F = IT \quad [4]$$

By substituting  $F$  for  $IT$ , equation 3 can be expressed as follows:

$$S = (100) e^{-KF} \quad [5]$$

where the symbols and units are the same as for equations 1 and 3.

Survival curves are plots of the mean values obtained from some congenial experiments for percentage bacterial survival ( $S$ ) as an exponential function of solar UV-A intensity ( $I$ ), or fluence ( $F$ ). The computed values are derived by the application of either equation 3 or 5.

## The solar reactors

The prototype solar units in the first stage of the experiment were installed on the roof of a university building (Figs 15 and 16). Artificially contaminated water in the storage reservoir (150 L) was pumped to the constant head tank, from where the flow would then be delivered by gravity to the solar reactor at desired flow rate.

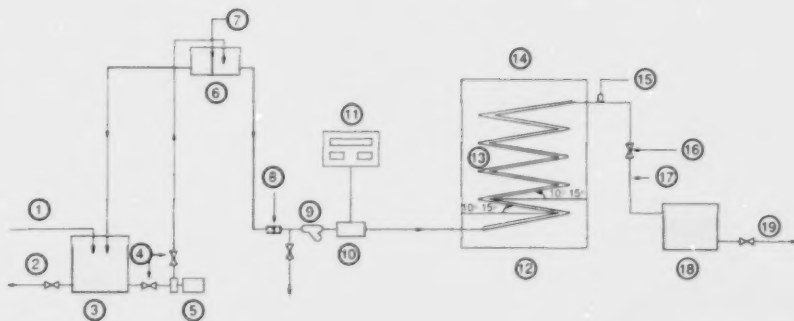


Fig. 15. Layout of type I solar reactor facility. 1, water feed; 2, drain; 3, storage reservoir containing contaminated water; 4, gate valve; 5, pump; 6, constant head-tank; 7, overflow; 8, flow regulator; 9, strainer; 10, flow meter; 11, digital flow meter panel and control; 12, solar reactor; 13, serpentine transparent tube; 14, inclined frame support (facing south); 15, air valve; 16, globe-valve; 17, effluent; 18, storage tank; 19, distribution.

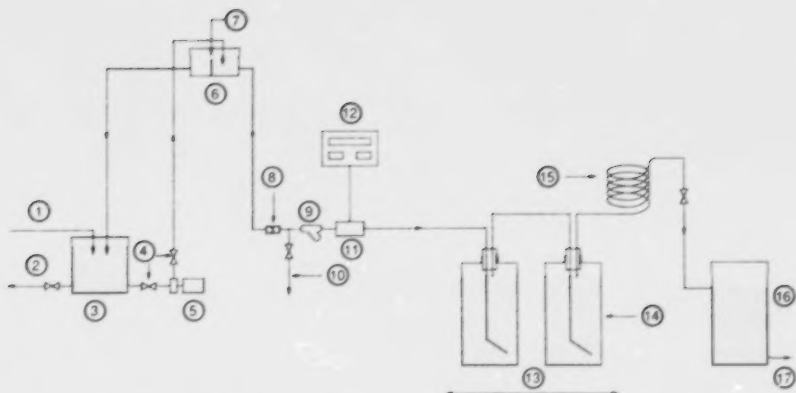


Fig. 16. Layout of type II solar reactor facility. 1, water feed; 2, drain; 3, storage reservoir containing contaminated water; 4, gate valve; 5, pump; 6, constant head-tank; 7, overflow; 8, flow regulator; 9, strainer; 10, drain; 11, flow meter; 12, digital meter panel and control; 13, solar reactor; 14, 4-L glass bottles; 15, transparent spiral tube; 16, storage tank; 17, distribution.

Solar reactor IA (Fig. 15) consisted of a serpentine-shaped, transparent tube made of Pyrex glass (borosilicate type) supported by a south-facing metal frame. The angle of inclination was set at  $35^\circ$  to approximate the latitude for Beirut ( $34^\circ$  N) for optimum solar irradiation. The dimensions of the glass tubing were as follows: total length, 13.4 m; outer diameter, 22 mm; wall thickness, 1.5 mm; capacity, 4.87 L; angle between segments,  $25 \pm 5^\circ$ . The latter feature prevented air-gap formation by inducing an upward flow of floating air bubbles. Solar reactor IB was a standby unit, used for comparison purposes. This unit differed from the first one in dimensions: total length, 12.0 m; outer diameter, 25 mm; wall thickness, 1.5 mm; and capacity 5.20 L. The two systems were independent and could be operated either separately or concurrently.

Type II solar reactors (Fig. 16) were developed for use at a later stage in the project to benefit from the expansion in the capacity of the transparent components exposed to sunlight within a minimum space. Solar reactor IIA consisted of an array of two Pyrex glass containers and a Pyrex glass helix. The capacity of each container was 4.23 L and the dimensions of the helix were as follows: total length, 10.52 m; outer diameter, 12 mm; wall thickness, 1.0 mm; capacity, 1.0 L. Thus, the total capacity of this reactor was 9.46 L. Solar reactor IIB differed in that an array of four containers were connected in series to the glass helix, thereby increasing the total capacity to 17.92 L, enhancing flow and output.

## Methodology

A fresh batch of 150 L of chlorinated tap water would be admitted into the storage reservoir 1 or 2 days in advance to allow the chlorine residual to diminish below 0.05 mg/L before its artificial bacterial contamination. The physicochemical quality of the water was established three times at intervals of 1 month (Table 2).

Between 1 and 2 h before each experiment, a batch of water would be

Table 2. Physicochemical quality of test water.

|                                            |                                  |
|--------------------------------------------|----------------------------------|
| pH                                         | 7.3 ± 0.0                        |
| Salinity                                   | 2.6 ± 0.4‰                       |
| Specific conductance (25°C)                | 4 435 ± 208 µmho/cm <sup>a</sup> |
| Total dissolved solids                     | 4 315 ± 275 mg/L                 |
| Total hardness (as CaCO <sub>3</sub> )     | 1 160 ± 100 mg/L                 |
| Calcium hardness (as CaCO <sub>3</sub> )   | 625 ± 25 mg/L                    |
| Magnesium hardness (as CaCO <sub>3</sub> ) | 530 ± 76 mg/L                    |
| Chloride (as Cl <sup>-</sup> )             | 2 075 ± 110 mg/L                 |
| Turbidity                                  | 1.3 ± 0.4 NTU <sup>b</sup>       |

Note: Average of three samples taken at monthly intervals from August to December 1986.

<sup>a</sup>1 mho = 1 S.

<sup>b</sup>NTU, nephelometric turbidity units.

contaminated with 0.2–0.7% fresh clarified sewage obtained from the main city sewer. This maintained the population of a specific test organism within a realistic concentration range of 50–5000 cells/mL. The sewage was freed from much of its suspended particles by settling or filtering, and was thoroughly mixed with water to ensure homogeneity. A pure culture of *Escherichia coli*, maintained on refrigerated nutrient agar slants before harvesting and transfer to lactose broth for overnight incubation at 35.5 ± 0.5°C, was used as a substitute for sewage in some of the experiments.

Each of the three selected fecal-indicator bacteria (coliforms, *Streptococcus faecalis*, and *E. coli*) was cultured for enumeration following standard bacteriological procedures (Difco Laboratories 1977; APHA 1985). The water inoculum ranged from 5 to 500 µL, and each set of three or four inoculated plates was run in duplicates. The water samples were rushed to the laboratory in the same building for immediate bacteriological analysis, avoiding their exposure to sunlight or even indoor illumination. Delays could yield false low results (Fujioka and Narikawa 1982; Acra et al. 1980; Acra et al. 1984). Coliforms and *E. coli* were assayed for viability by surface streaking on desoxycholate lactose agar, whereas *S. faecalis* was assayed on KF *Streptococcus* agar (both media from Difco Laboratories, Detroit, MI, USA, or Bio-Merieux, Charbonnieres les Bains, France).

Solar UV-A intensity received on the surfaces of the reactors was measured in triplicate at timed intervals during each experiment with the same digital radiometer described earlier. Fluence (*F*) was calculated from the average intensity and the exposure time as explained before.

Solar irradiation experiments were generally carried out between 0930 and 1330. Sampling and measurement of the desired parameters was carried out at short intervals (25–30 min) because of the nonuniformity in the radiation intensity. Irradiated and nonirradiated samples of water were collected in duplicates from the inlet and outlet ports of the reactors: one for an immediate temperature reading and the other in a sterile container for bacteriological testing. At the same time, average values for several readings of the flow rate and the solar UV-A intensity were recorded for each interval, as well as the volume of effluent water. The residence time for each interval, assumed to represent the solar exposure time, was calculated from the relevant flow rate and capacity of the experimental reactor. In all experiments, the readings for the first interval were discarded, and only the overall

means for the intervals per experiment were pooled to provide data for the computations based on the equations given before. Averaged data for the influent and effluent samples for a group of congenial experiments were considered for the evaluation of each reactor to provide more reliable results by stabilizing the variances. The Statistical Conversational Package for the Social Sciences (SCSS) was used for data analysis on an IBM VM-370 computer.

## Results

Six trial experiments were run in mid-1986, after which the two prototype units with solar reactors IA and IB functioned satisfactorily. The experiments with these two reactors were 11 for coliforms, 11 for *S. faecalis*, and 6 for cultured *E. coli* (13 August–18 December 1986). In addition, four experiments were run on reactors IIA and IIB for coliforms (18 December 1986–22 January 1987). As the experimental results yielded by the solar reactors IA and IB were found to be comparable, the data for these two units were pooled for statistical analysis and evaluation.

The data were recorded considering the bacterial counts as the dependent variable and water temperature, flow rate, and solar UV-A intensity as the independent variables (see sample data sheet in Appendix 6). The data pertaining to solar reactors IA and IB for coliforms, *E. coli*, and *S. faecalis* are summarized in Appendices 7, 8, and 9. These statistics were applied in equation 5 for computing the exponential relationship between solar UV-A fluence ( $F$  or  $IT$ ) and percentage bacterial survival ( $S$ ). This approach tends to eliminate any bias introduced by experimental errors and uncontrollable fluctuations in the experimental conditions. It also considers uniform flow (plug flow) through the reactors and, consequently, the exposure time calculated for each interval on this basis. Mean preliminary values obtained with reactors IIA and IIB are shown in Appendix 10.

The percentage survival curve for each of the three fecal indicator bacteria relate to the computed data obtained with reactors IA and IB (Figs 17, 18, and 19). In each case, the corresponding exponential equation is recorded together with the specific values for the statistical significance levels. In all three cases, the  $p$  value is below 0.001, indicating a high significance level. Insufficient data for reactors IIA and IIB precluded computation of the exponential survivals and presentation of the graphs.

Samples of the effluent from the reactors were kept periodically at room conditions or in the dark for a day or more to check for bacterial regrowth. Regrowth was not observed upon culturing on the usual media in any of these cases or in the batch system.

## Discussion

Data from previous batch-inactivation experiments provided baseline information and criteria for the design, operation, and expected performance of the continuous-flow prototypes (Acra et al. 1980; Acra et al. 1984). They included the following:

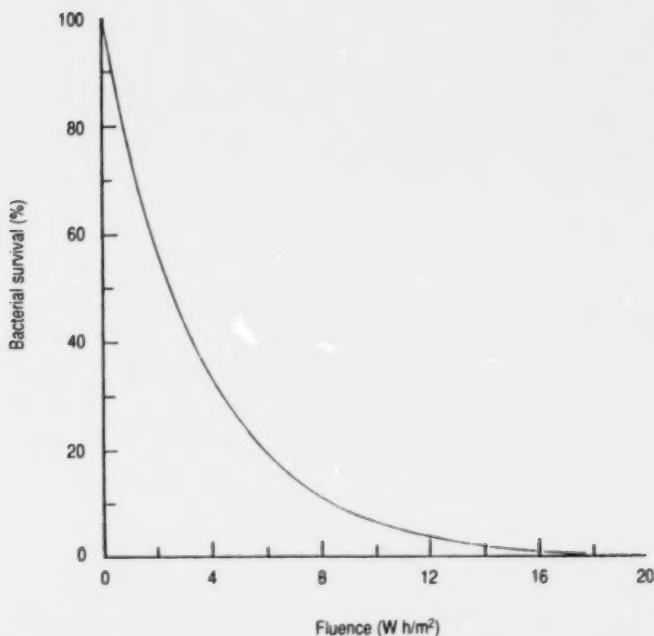


Fig. 17. Survival of coliforms as a function of solar UV-A fluence. Based on data from Appendix 7 and the derived exponential equation 3:  $S = 100e^{-0.279 F}$  ( $n = 12$ ,  $r = -0.946$ ,  $p < 0.001$ ).

- nature, density, and relative sensitivity of indicator and pathogenic microorganisms to be tested;
- presence of nutrients or inhibitory factors (e.g., water temperature and predators);
- solar intensity and effective radiation wavelengths;
- penetration power of the effective radiation and, hence, the transparency and wall thickness of the reactor material, as well as the depth of the water to be penetrated;
- the optical characteristics of the water and its interfering constituents (e.g., colouring substances, soluble salts, and suspended particles); and
- design, configuration, hydraulic loading, and orientation of the solar reactor.

Other variables that should be accounted for in similar studies are summarized in Table 3.

A constant head with a low to moderate pressure was deemed necessary to maintain a uniform inflow of feed water that could be regulated to provide an adequate exposure time for solar decontamination. The strainer (Figs 15 and 16) was intended to supplement prefiltration of the feed water, if needed.

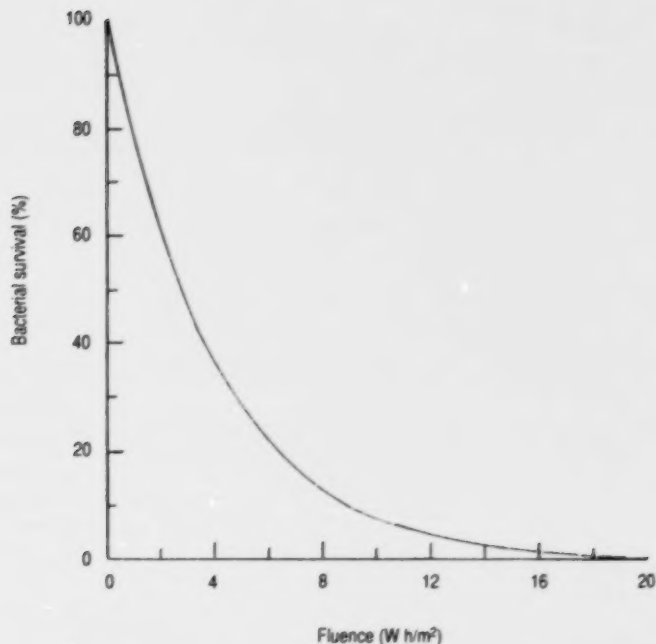


Fig. 18. Survival of *Streptococcus faecalis* as a function of solar UV-A fluence. Based on data from Appendix 8 and the derived exponential equation 3:  $S = 100e^{-0.259 F}$  ( $n = 12$ ,  $r = -0.949$ ,  $p < 0.001$ ).

Solar reactors IA and IB were constructed with Pyrex glass tubing for three reasons:

- borosilicate glass is an efficient transmitter of solar radiation at wavelengths longer than 290 nm;
- it is available locally and can be moulded thermally by a glassblower; and
- it is sufficiently durable to the weathering effects of sunlight and scratches.

Plastics possessing equal or better features, provided such materials do not add to the costs and can be locally moulded into shape, can also be used. The two potentially critical features pertaining to the wall thickness of the glass components and the water depth would not significantly attenuate the incident solar radiation in the case of these two types of reactors. The slight upward inclination of the serpentine- and helical-shaped glass tubings was intended to prevent the formation of air gaps that would interfere with the flow of the water. A rise in water temperature upon exposure to sunlight would decrease the solubility of oxygen and thus release it from solution with no possibility for replenishment from the atmosphere. Such a preventive configuration of the reactors allows no gaps by the trapped gases. However, the ecological impact of the greatly diminished residual gases on the microbial population in the warmed water is subject to speculation.

The south-facing orientation of solar reactors IA and IB and their inclination

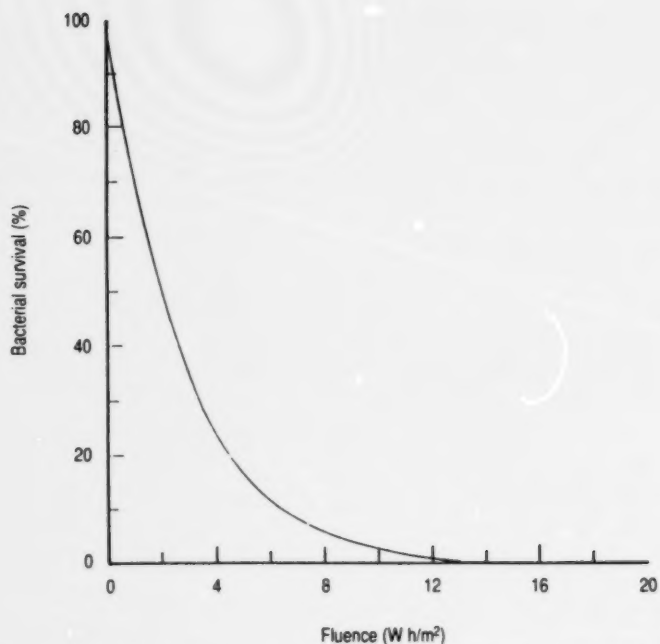


Fig. 19. Survival of *Escherichia coli* as a function of solar UV-A fluence. Based on data from Appendix 9 and the derived exponential equation 3:  $S = 100e^{-0.362 I t}$  ( $n = 7$ ,  $r = -0.984$ ,  $p < 0.001$ ).

fixed at 35° from the horizontal provided the necessary conditions for the optimal influx of solar radiation. Other angles of inclination could prove just as effective because of the rounded shape of the tubes, except for upright positions for fear of shading at periods of high solar altitude. The situation is somewhat different in the case of solar reactors IIA and IIB as the components were made to stand upright. It is possible, however, to keep them inclined with appropriate supports. While designing the prototype solar reactors, the criteria that would enhance the transmittance of the most effective biocidal wavelengths of solar radiation was considered. The design of the various types of reactors with artificial UVR sources, their hydraulic characteristics, and performance would be a useful information source, although they differ from solar reactors with respect to radiation source and orientation (Qualls et al. 1983; Severin et al. 1984; Kreft et al. 1986; White et al. 1986; Scheible 1987).

The flow of contaminated water through the reactors was maintained within 4–37 L/h, which corresponded to a range of exposure time of 66–8 min (Appendices 7–10). To minimize the cost/benefit ratio, it would be important to maximize the flow rate and, thus, the output of the facility. This may be accomplished, at least in part, by either increasing the capacity of the reactor without significantly diminishing the transmitted solar energy or replicating the modules, i.e., increasing the number of reactors connected in series (Fig. 16).

The test water used in this study can be described as saline, hard, and slightly

Table 3. Variables affecting the disinfection of drinking water by solar UV-A radiation (320–400 nm).

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|                                                            |
|------------------------------------------------------------|
| 1. Intensity                                               |
| Latitude and geographic location                           |
| Time of year (season, month, solar angle)                  |
| Time of day                                                |
| Metereological conditions (cloudiness, humidity, rainfall) |
| 2. Exposure                                                |
| Time                                                       |
| Flow rate                                                  |
| 3. Transmitting media                                      |
| Solar unit                                                 |
| Material (kind and thickness)                              |
| Conduit (dimensions)                                       |
| Contaminated water                                         |
| Suspended particles (turbidity)                            |
| Temperature                                                |
| Salinity                                                   |
| Dissolved oxygen and nutrients                             |
| Predators                                                  |
| Disinfectant                                               |
| 4. Target organisms                                        |
| Types and strains                                          |
| Concentration                                              |

---

turbid (Table 2). It also contained trace amounts of organic matter contributed by the added sewage or lactose broth in the case of *E. coli* culture. Certain water characteristics could influence the survival of microorganisms and, hence, modify the inactivation effect of sunlight. These factors include inorganic salts, organic nutrients, predators, bacteriophages, bacterial toxins, and surface attachment (Carlucci and Pramer 1959; Nabbut and Kurayiyah 1972; Chamberlin and Mitchell 1978; Gaudy and Gaudy 1980; McCambridge and McMeekin 1981; Moss and Smith 1981). Another important factor is associated with the presence of suspended particles that would shield the microorganisms from exposure to radiation (Qualls et al. 1983, 1985; Scheible 1987). Because of the low turbidity levels of the contaminated waters used ( $1.3 \pm 0.4$  Nephelometric Turbidity Units [NTU]), sunlight attenuation by absorption in the effective wavelengths is not expected to be significant.

Stresses imposed upon the test organisms by one or more of the potentially detrimental factors mentioned (loss of dissolved gases, variations in the water pH, temperature, etc.) could have enhanced the solar inactivation effect. Nevertheless, the bactericidal action of solar UVR appears to play a dominant role, and a synergistic action is desirable from a practical viewpoint.

We inferred from trial experiments with both the batch and continuous-flow systems that high-density bacterial populations show lower sensitivity to solar radiation compared with those with a low or moderate density. This phenomenon was reflected in the need for prolonging the exposure time for bacterial populations in excess of a few thousand cells per millilitre (Gaudy and Gaudy 1980; Abshire

and Dunton 1981). These facts have consequently prompted this study to avoid the use of the conventional bacterial density range of  $10^8$ – $10^{10}$  viable cells/mL (Nabbut and Kurayiyah 1972; McCambridge and McMeekin 1981; Moss and Smith 1981; Tyrrell and Souza-Neto 1981).

The use of normal intestinal bacteria as indicators of fecal pollution is universally acceptable for monitoring and assessing the microbial quality of water supplies (Feachem et al. 1983; WHO 1987). The bacteria used in this study were selected because they are more resistant than the pathogens to disinfection by physical or chemical agents. Their photoinactivation is, therefore, an apropos assumption that the pathogenic bacterial contaminants in water would also have been similarly affected.

The spectrum curve for the inactivation of coliforms was determined (Fig. 20) based on the expression that relates the relative bacterial inactivation rate (percent)

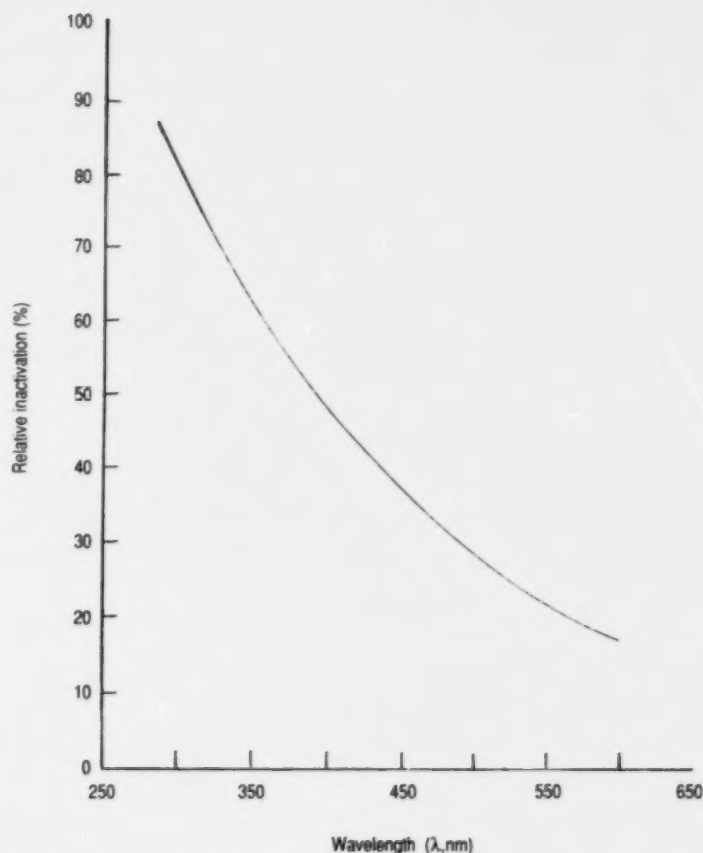


Fig. 20. Action spectrum for the inactivation of coliforms in contaminated water exposed to sunlight in coloured transparent glass containers. Relative inactivation (%) =  $398e^{-0.0051\lambda}$  ( $n = 6$ ,  $r = -0.925$ ,  $p < 0.01$ ).

with the wavelength of transmitted light (Acra et al. 1980; Acher 1985). Relative inactivation is in reference to the inactivation rate at 260 nm. Locally made glass jugs of different colours and hues were used during the batch experiment. The spectral transmission curves were determined spectrophotometrically from specimens of each of the coloured glasses. The wavelengths corresponding to 50% light transmittance were used to compute the exponential equation. It is inferred from this curve that the relative photoinactivation rate decreases exponentially as the wavelength of sunlight increases. In the most active UV-A region, for example, the relative inactivation rates range from 75 to 50% at 320 and 400 nm, respectively. Those for the violet and blue regions are lower, ranging from 50% at 400 nm to 30% at 490 nm. At the midpoints in these two regions, the relative inactivation rates diminish from 60% at 360 nm to 40% at 445 nm. This accounts for an inactivation efficiency of about 1.5 times for UV-A compared with that for violet-blue light.

The curve in Fig. 21 was derived from the same set of data for the coliform action spectrum. The time required for sunlight to inactivate 99.9% of the initial

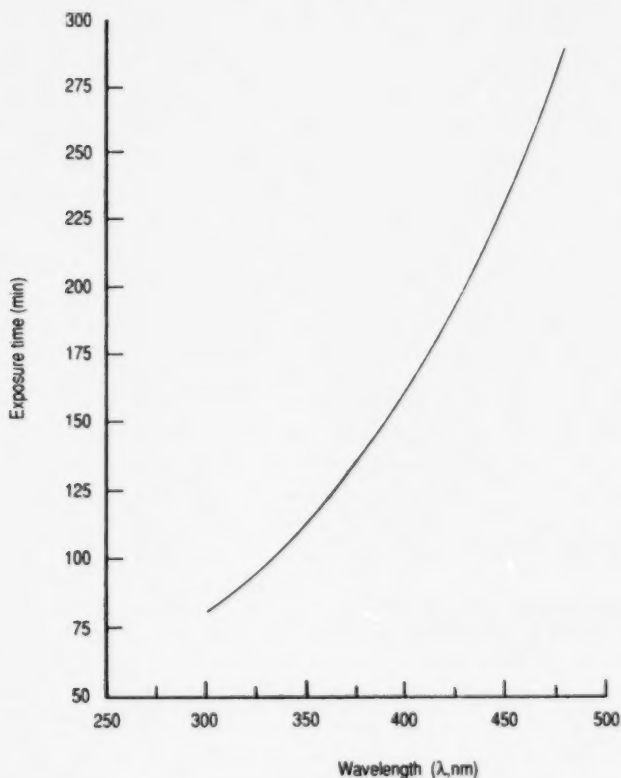


Fig. 21. Time required to inactivate 99.9% ( $T_{99.9}$ ) of coliforms in contaminated water exposed to sunlight in coloured transparent glass containers, as a function of wavelength.  $T_{99.9} = 9.4e^{0.0071\lambda}$  ( $n = 5$ ,  $r = 0.992$ ,  $p < 0.001$ ).

coliform cells ( $T_{99.9}$ ) increases exponentially with wavelength. The  $T_{99.9}$  values for solar UV-A range from 90 min at 320 nm to 165 min at 400 nm. For the violet-blue region, it rises to 310 min at 490 nm. However, sunlight is polychromatic and, as such, may introduce the complicating factor of synergism or antagonism as opposed to monochromatic light or a confined wavelength band.

As stated earlier, solar UVR at wavelengths below 290 nm does not reach ground level. In addition, radiation in the UV-B spectral region (280–320 nm) is not transmitted through ordinary glass. Pyrex glass, however, can transmit low levels of UV-B at wavelengths greater than 300 nm. Attenuation through absorption by the test water in glass containers or that flowing through a solar reactor would achieve further reductions in the incident UV-B radiation. It can be assumed, then, that natural UV-B radiation plays an insignificant role in solar inactivation of bacteria wherever glassware in the form of containers or tubes is used as solar reactors. This, together with the preceding information derived from the coliform action spectrum, leads to the conclusion that the natural UV-A radiation plays the dominant role in the photodecontamination process as applied in these studies.

The mean values of the measured parameters (bacterial survival, solar UV-A intensity, flow rate, and water temperature) are summarized in Appendices 7, 8, and 9, for the selected fecal indicator bacteria (*E. coli*, *S. faecalis*, and coliforms). The statistics for percentage bacterial survival ( $S$ ) were exponentially regressed against those for fluence ( $F$ ) according to equation 5. Thus, an adequate set of computed values for  $S$  and  $F$  were obtained for plotting the survival curve relevant to each test organism (Figs 17–19). If desired, the computed values for exposure time ( $T$ ) or radiation intensity ( $I$ ) can be derived by substitution in equation 4. However, the fitness of the experimental mean values with first-order kinetics is verified in the case of each organism by the high levels of significance ( $p < 0.001$ ).

The summarized fluence values (Table 4) needed to inactivate each of the test organisms to levels of 90, 99, and 99.9% and their respective inactivation rate constants ( $k$ ), show that *S. faecalis* required relatively more solar UV-A fluence for photoinactivation than the other two indicator bacteria; *E. coli* was the most sensitive. The  $T_{99.9}$  fluence values, for instance, were approximately 27, 25, and 19  $W\ h/m^2$  for *S. faecalis*, coliforms, and *E. coli*, respectively. Analysis of variance of the experimental mean values for the percentage survival versus solar UV-A fluence (Appendix 11) showed a statistically significant difference. However, no significant correlation was observed between the mean water temperature values and percentage bacterial survival at the 0.05 significance level. This agrees with reports that UV sensitivity of bacteria is only slightly influenced by temperature in the range of 5–37°C (Cheremissinoff et al. 1981). For an average solar UV-A

Table 4. Solar UV-A fluence required to achieve specified percentage inactivation levels of three fecal-indicator bacteria.

| Test organism                 | Fluence ( $W\ h/m^2$ )<br>required to inactivate: |       |       | Exponential<br>inactivation<br>rate ( $K$ ) |
|-------------------------------|---------------------------------------------------|-------|-------|---------------------------------------------|
|                               | 90%                                               | 99%   | 99.9% |                                             |
| <i>Streptococcus faecalis</i> | 8.90                                              | 17.80 | 26.72 | – 0.259                                     |
| Coliforms                     | 8.24                                              | 16.59 | 24.74 | – 0.279                                     |
| <i>Escherichia coli</i>       | 6.36                                              | 12.72 | 19.08 | – 0.362                                     |

intensity on a horizontal target at midday in Beirut of  $10 \text{ W/m}^2$ , these fluence values would correspond to exposure times ( $T$ ) of 160, 150, and 115 min, respectively. The  $T_{99.9}$  value of 150 min for coliforms falls within the range of the corresponding mean values obtained for the same organism in a previous study involving a batch exposure system, which yielded  $T_{99.9}$  values of 90 min at 320 nm and 165 min at 400 nm (Fig. 21).

In additional single experiments run simultaneously by the batch system using contaminated water in 300 mL, round Pyrex flasks (one for each type of organism inoculated), the time required for complete photoinactivation of certain enteric pathogens was as follows: *Salmonella paratyphi*, 90 min; *E. coli*, 75 min; *Salmonella typhi* and *Salmonella enteritidis*, 60 min each; *Salmonella flexneri*, 30 min; and *Pseudomonas aeruginosa*, 15 min. It would be justifiable to infer from these findings that:

- the time required for complete inactivation by sunlight of fecal bacteria is dependent, among other factors, on the type of microorganism;
- the fecal-indicator bacteria are more resistant to the injurious effects of sunlight than the enteric pathogens;
- among the group of fecal-indicator bacteria considered, *S. faecalis* is the most tolerant, whereas *E. coli* is the least tolerant; and
- among the group of enteropathogenic bacteria considered, *S. paratyphi* is the most tolerant and *P. aeruginosa* is the least tolerant.

The comparisons made between the experimental results cannot be sound and valid unless the potentially significant variables are strictly controlled by proper experimental design. For instance, the experimental data involving the use of a pure culture of *E. coli* (Appendix 9, Fig. 19) contrasts with the use of sewage as a source for water contamination in the case of coliforms and *S. faecalis* (Appendices 7 and 8, respectively). Nevertheless, sewage-contaminated water is more realistic for experiments in these cases.

Differences in experimental design, experimental conditions, and measurement units could add complexity to comparisons with data reported elsewhere, in particular for those studies based on the use of artificial, monochromatic UVR (Abshire and Dunton 1981; Kubitschek and Doyle 1981; McCambridge and McMeekin 1981; Chang et al. 1985; Haeder 1986) in contrast to those based on filtered sunlight (Jagger 1975; Tyrrell and Souza-Neto 1981). For instance, the germicidal action of solar UVR has been studied on *E. coli* and coliforms in sewage-treatment lagoons for which the measurement of solar radiation was restricted to the UV-B spectrum (Calkins et al. 1976; Moeller and Calkins 1980). These investigations were based on the grounds that natural UV-B radiation with its relatively strong biocidal effects can penetrate the exposed surfaces of the wastewater. However, concomitant and potential effect of the solar UV-A was not considered. The inference that fecal streptococci were more resistant to sunlight than fecal coliforms has also been reported (Fujioka and Narikawa 1982), but without enough solar UVR data to compare with this study.

On the basis of their relative susceptibility to solar radiation, the bacteria that occur in seawater have been ranked as follows (McCambridge and McMeekin 1981): *Klebsiella pneumonia* > *E. coli* > *Salmonella typhimurium*, *Streptococcus*

*faecium*, and *Enterobacter aerogenes*. In addition, using artificial UV-B radiation and microbial suspensions in buffered sterile water, the resistance of some microorganisms has been ranked as follows (Chang et al. 1985): *A. castellanii* cysts > *Bacillus subtilis* spores > simian rotavirus > standard plate count > *S. faecalis* > total coliforms > *E. coli* > *Streptococcus aureus* > *Shigella sonnei* > *S. typhi*. It has been reported that the inactivation of virus, bacterial spores, and amoebic cysts required 3–4, 9, and 15 times, respectively, the UV-B fluence required for *E. coli* (Chang et al. 1985). Similar lists have been published for UV-C radiation showing that some mould spores required 50 times the fluence required for *E. coli* at 254 nm (Legan 1980).

For Beirut and other localities with similar conditions, the predicted exposure times required to inactivate the three indicator bacteria to a specified percentage level under various solar UV-A intensities are shown in Figs 22–24 (Appendices 12–14). For instance, 62 min is the predicted required exposure time (*T*) to inactivate 99% of the coliform bacteria in water with an incident solar UV-A

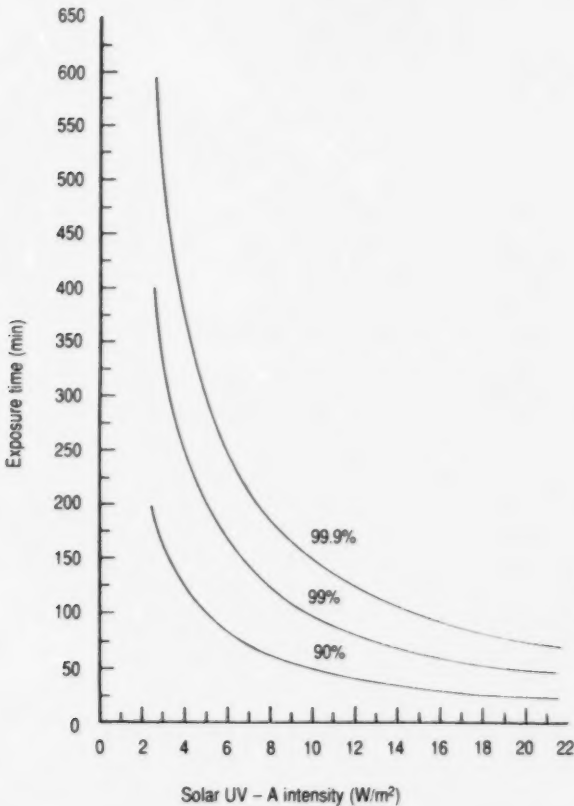


Fig. 22. Time required to inactivate 90, 99, and 99.9% of coliforms in contaminated water as a function of solar UV-A intensity (data from Appendix 12).

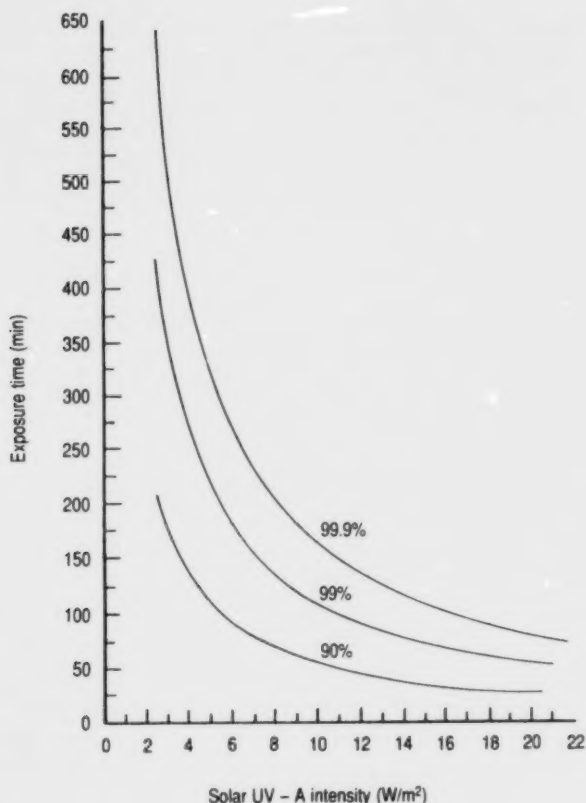


Fig. 23. Time required to inactivate 90, 99, and 99.9% of *Streptococcus faecalis* in contaminated water as a function of solar UV-A intensity (data from Appendix 13).

intensity ( $I$ ) of  $16 \text{ W/m}^2$ . This can also be expressed in terms of fluence ( $F = It$ ) as  $16.5 \text{ W h/m}^2$ . The three commonly used percentage inactivation levels ( $T_{90}$ ,  $T_{99}$ , and  $T_{99.9}$ ) are related mathematically as follows:

$$T_{99.9} = 1.5(T_{99}) = 3(T_{90}) \quad [6]$$

## Conclusions and recommendations

The prototype solar reactors IA and IB (Fig. 15) operated and performed satisfactorily during the experiments. However, productivity could be increased by increasing reactor capacity or replicating reactor modules. An increase in reactor capacity magnifies the dimensions of the unit. Transparent reactor tubings with internal diameters of 10–15 cm could be practical if affordable. A 10-fold increase in diameter would allow for a 100-fold increment in capacity and, thereby, in output.

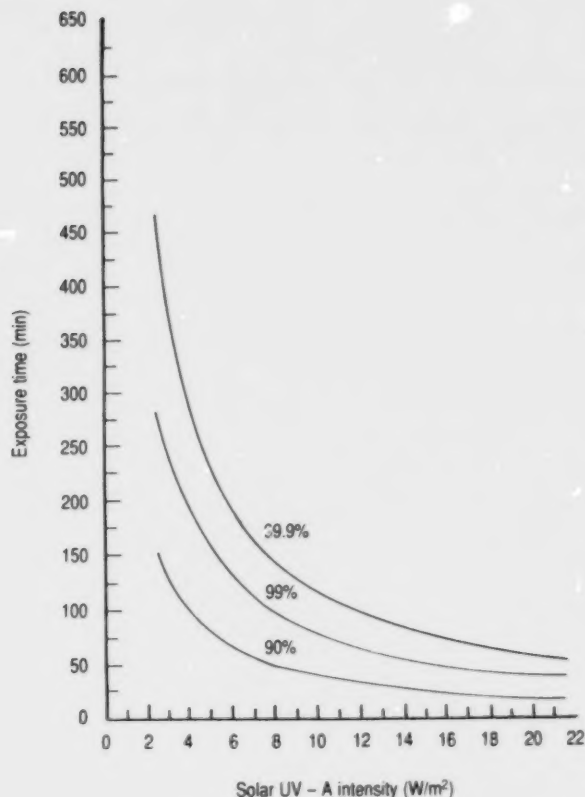


Fig. 24. Time required to inactivate 90, 99, and 99.9% of *Escherichia coli* in contaminated water as a function of solar UV-A intensity (data from Appendix 14).

Strict adherence to the minimum fluence requirement for, say, a  $T_{99.9}$  level of photoinactivation of the selected fecal indicator bacteria is mandatory. In fact, an additional fluence requirement of 10–20% is highly recommended as a safety margin. The kind of bacterium to serve as a “reference” for solar disinfection should be related to the relative sensitivity of the organism to solar UV-A.

*Streptococcus faecalis* has proven in experiments to be the most resistant of the three fecal-indicator bacteria (Table 4). It has also been shown to be more resistant to photoinactivation than several of the enteropathogenic bacteria (McCambridge and McMeekin 1981). Consequently, enumeration of *S. faecalis* is proposed as a suitable tool for designing or monitoring water-disinfection processes by sunlight. Therefore, a minimum UV-A fluence of  $17.8 \text{ W/m}^2$  would be required to decontaminate water to a  $T_{99.9}$  level, to which a safety margin of  $1.8\text{--}3.6 \text{ W/m}^2$  should be added.

The type II solar reactor possesses some advantageous features with potential for

- increased capacity and output with space conservation;

- removal of residual turbidity by settling in the first one or two containers that can be readily removed from operation for cleaning; and
- making locally the transparent containers or cylinders.

Although a thorough evaluation of these reactors was not possible, the preliminary results (Appendix 10) seem to be comparable to those obtained with reactors 1A and 1B.

Growth of phytoplankton that attach to the inner walls of the solar reactors leading to diminished light transmission was one of the observed potential problems. No visible growth occurred, possibly because of the loss of soluble gases and lack of atmospheric contact for replenishment, the absence of sufficient quantities of nutrients, and the elimination of conditions for commensalism, among other minor factors, which seem to be the main reasons for interface attachment (Marshall 1978). In addition, microorganisms attached to the inner surfaces of the tubes are likely to be more susceptible to incident radiation.

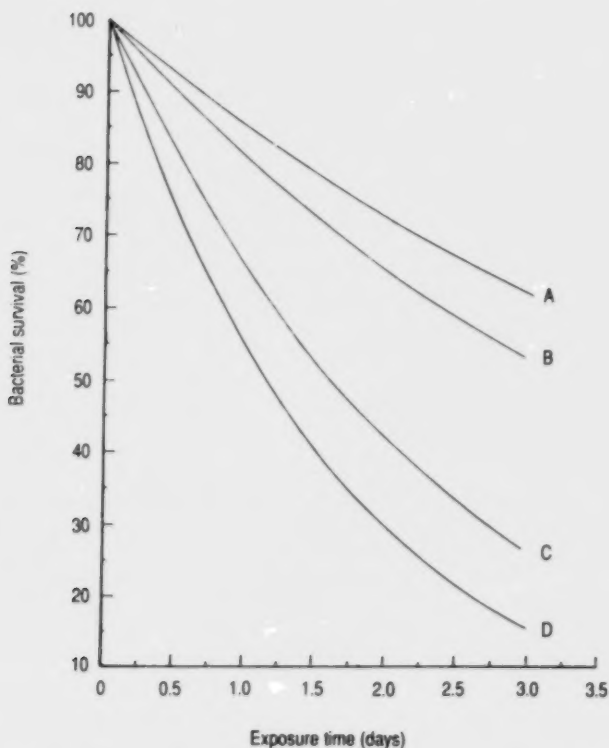


Fig. 25. Comparative survival of bacteria in estuarine water exposed to sunlight. Computed from McCambridge and McMeekin (1981) based on the derived exponential equation 3: (A) *Streptococcus faecium*:  $S = 100e^{-0.160T}$  ( $n = 6$ ,  $r = -0.962$ ,  $p < 0.01$ ); (B) *Salmonella typhimurium*:  $S = 100e^{-0.211T}$  ( $n = 6$ ,  $r = -0.938$ ,  $p < 0.01$ ); (C) *Escherichia coli*:  $S = 100e^{-0.432T}$  ( $n = 5$ ,  $r = -0.896$ ,  $p < 0.05$ ); (D) *Klebsiella pneumoniae*:  $S = 100e^{-0.604T}$  ( $n = 6$ ,  $r = -0.938$ ,  $p < 0.01$ ).

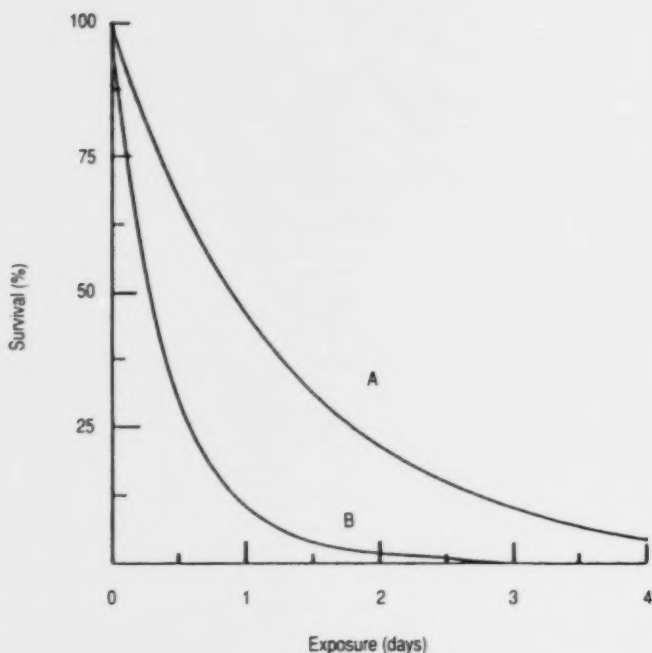


Fig. 26. Survival of *Salmonella typhi* in autoclaved (A) and untreated (B) seawater. Computed from Nabbut and Kurayiyah (1972) based on the derived exponential equation 3: (A):  $S = 100e^{-0.772t}$  ( $n = 5$ ,  $r = -0.992$ ,  $p < 0.001$ ,  $T_{99} = 6$  days); (B):  $S = 100e^{-2.4097t}$  ( $n = 5$ ,  $r = -0.972$ ,  $p < 0.01$ ,  $T_{99} = 2$  days).

Under field conditions, it would be essential to limit the disinfection process to that part of the day with sufficiently bright sunlight. The alternating "on" and "off" operations could be handled in one of the following ways:

- manually, which is cumbersome and time consuming;
- by means of a timing device, which is rather cheap; and
- by means of an electronic photocell or radiometer that would automatically regulate the flow of feed water in proportion to solar intensity and would cut off or start the flow at preset radiation levels — its higher cost may be justified for large-scale installations.

Some of the difficulties observed in the photobiological literature are the lack of uniformity in experimental design, radiation units adopted, and mode of data presentation. This could lead to some confusion. For example, the exponential regression curves (Figs 25–27) are suggested as an appropriate alternative to the complex tabulated data from which they were computed (Nabbut and Kurayiyah 1972; Larkin et al. 1976; McCambridge and McMeekin 1981). In addition, information on the effect of UV-A on other waterborne microorganisms is scanty. However, some indirect evidence corroborates the role that sunlight plays in the survival of a variety of microorganisms, including viruses (Geldreich 1972; Calkins et al. 1976; Bitton et al. 1986).

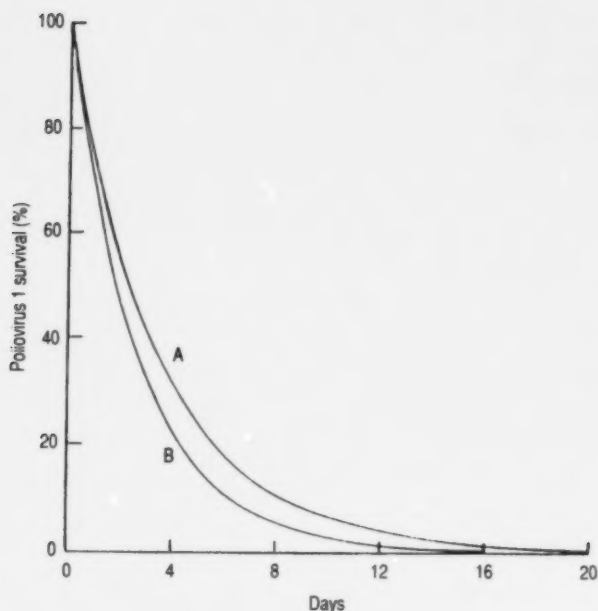


Fig. 27. Survival of poliovirus 1 on the surface of lettuce sprayed with inoculated sewage sludge (A) and sewage effluent (B). Computed from Larkin et al. (1976) based on the derived exponential equation 3: (A)  $S = 100e^{-0.272T}$  ( $n = 10$ ,  $r = -0.925$ ,  $p < 0.001$ ,  $T_{99} = 17$  days); (B)  $S = 100e^{-0.372T}$  ( $n = 7$ ,  $r = -0.975$ ,  $p < 0.001$ ,  $T_{99} = 12$  days).

Special consideration should be given in future experiments to the potential for solar decontamination of water inoculated with such organisms as *Legionella* spp., which seems to be susceptible to artificial UV-B radiation (Antopol and Elner 1979; Gilpin et al. 1985; Voss et al. 1986), cholera bacillus, schistosomes (cercariae), and enteric viruses. Should these and similar organisms prove to be sensitive to the biocidal effect of solar radiation, then a great public health issue would have been resolved.

Treating water with large doses of sodium hypochlorite or iodine solutions and subsequent exposure to solar radiation, aptly designated as "halosol" technique, was developed at the American University in Beirut (1979–1982). It was intended to be an efficacious disinfection method for small volumes of heavily polluted water with the concomitant removal of excess halogen by solar irradiation. This would also help to avoid taste and odour complaints.

### Batch system

During the batch experiments, up to 5 L of halogenated water containing chlorine or iodine residuals of  $\leq 7$  mg/L were exposed to sunlight in transparent containers made of colourless or blue-tinted glass or plastic, showing efficient halogen removal. For instance, the  $T_{50}$  and  $T_{99}$  values for dechlorination were 11 and 72 min (32 and 215 min for deiodination), respectively. In contrast, the decay reaction occurring under normal room illumination was slower, and complete darkness (or the use of dark brown containers) retarded it. The percentage mean values for the chlorine residuals decomposed photochemically, when regressed exponentially against the specific wavelengths of light that yield at least 50% transmittance, revealed that

- the relative effectiveness of solar radiation decreased with wavelength in the 310–550 nm range and
- most of the chlorine residual decomposed photochemically was largely accounted for by the solar UV-A radiation (Fig. 28).

An inverse linear relationship between total chlorine residual (TCR, percent) and chlorinated water temperature ( $T$ ) in the range of 20–70°C was observed. A mean value of 4.7% drop in the initial TCR for each 10°C rise in the temperature above 20°C was obtained. The relevant linear expression is as follows:

$$\text{TCR} = 109.5 - 0.47T \quad [7]$$

Because the rise in temperature of water exposed to sunlight did not generally exceed 10°C in experiments run up to 180 min, the major photodechlorination effect was considered to be due to solar radiation. The relative rates for raising chlorinated water temperature in containers shielded with coloured plastic cylinders and exposed to sunlight were as follows: colourless (100%) > red (83%) > green (71%) > yellow (69%) > orange (62%) > blue-green (58%) > blue (46%).

As TCR diminished with length of exposure, initial pH also decreased. This is

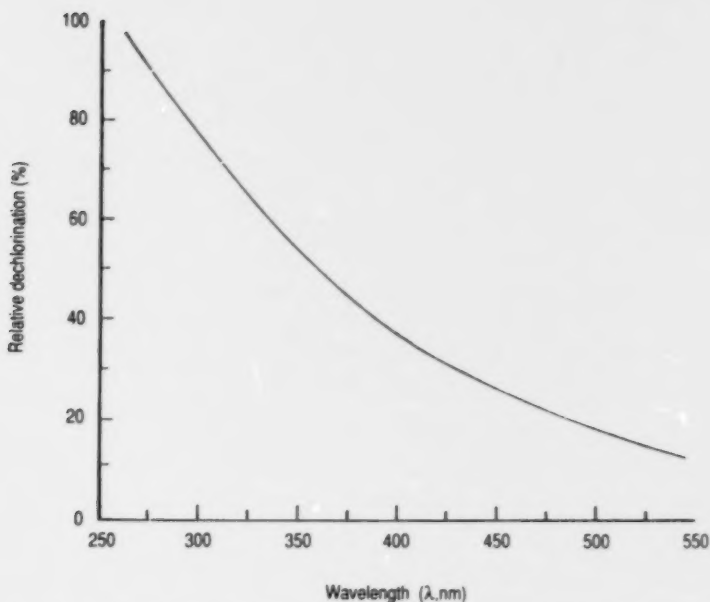


Fig. 28. Relative dechlorination (%) of water exposed to solar radiation in coloured glass containers as a function of wavelength. Relative dechlorination (%) =  $612e^{-0.007\lambda}$  ( $n = 5$ ,  $r = -0.914$ ,  $p < 0.05$ ).

presumed to be induced by the phototransformation of the weak HOCl to the strong HCl, liberating oxygen (Driver 1960):



The linear expression derived from the experimental data for this effect was as follows:

$$\text{pH} = 7.78 + 10^{-3} \text{ TCR} \quad [8]$$

It was found that an intervening glass reduced the photodechlorination process, which was 2.5–3 times more efficient for containers placed in front of a closed glass window than for those placed behind. For instance,  $T_{99}$  values for percentage chlorine reduction were 80 and 230 min for containers placed in front and behind the window, respectively.

Photodechlorination in round 3-L flasks was found to be 10% more efficient ( $T_{99} = 117$  min) than for conical flasks ( $T_{99} = 130$  min). This difference may be due to the more favourable angles of incidence of solar radiation on spherical containers, which intercept light equally from all directions.

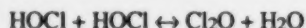
From the batch experiment results, it was concluded that some of the important advantages of the halosol technique are the following:

- enhancement of the biocidal action by the combined effects of the free residual halogens, sunlight, and the possible involvement of singlet oxygen;

- removal of objectionable tastes and odours produced by high halogen doses; and
- possible role of solar radiation in minimizing the formation of THM.

## Dechlorination kinetics

The reactions of halogens with water as a function of pH and temperature could be complicated by the formation of a variety of species. The formation of chlorine monoxide ( $\text{Cl}_2\text{O}$ ), for instance, as a very reactive species has been postulated to occur at a pH below 8 (Reinhard and Stumm 1980):



The mechanism of photodecomposition of the diverse halogen species formed also becomes equally complex, particularly by the potentially different effects of the polychromatic characteristics of sunlight. Nevertheless, a first-order kinetic reaction for the solar dehalogenation process has been assumed on the basis of an exponential relationship expressed as follows:

$$C/C_0 = e^{-KIt} \quad [9]$$

where  $C_0$  is initial halogen residual concentration (milligrams per litre),  $C$  is halogen residual concentration (milligrams per litre) after exposure,  $C/C_0$  is the ratio of halogen residuals,  $K$  is the photodecomposition rate constant (square centimetres per microwatt minute,  $\text{cm}^2/\mu\text{W min}$ ),  $I$  is the incident solar UV-A intensity (microwatts per square centimetre),  $t$  is exposure time or photoreaction time (minutes), and  $e$  is equal to 2.7182.

As for equations 3 and 5, this expression may be transformed:

$$R = (100) e^{-KIt} \quad [10]$$

$$R = (100) e^{-KF} \quad [11]$$

where  $R$  is the halogen residual remaining (percent) and  $F$  is fluence (watt hours per square metre or microwatt minutes per square centimetre). Other symbols and units are as previously defined for equation 9.

The exponential decay curves representing the decrease in chlorine concentration as a function of solar UV-A radiation intensity or fluence were based on the mean values obtained for a group of experiments run under varied conditions of sunlight and exposure time. The computed values were derived through either equations 10 or 11.

## Methodology

Type I solar reactors (Fig. 15) were used independently to test the photodehalogenation process in continuous-flow systems. Commercial sodium hypochlorite solution (Clorox, Clorox Co., Casa Mitjana, Spain) was added gradually to the 150 L of tap water in the storage reservoir. A contact time of 30 min or more was allowed for the completion of any oxidative reactions. The same test water was used, but some differences in quality were noted (Table 5).

Table 5. Physicochemical quality of test water.

|                                            |                              |
|--------------------------------------------|------------------------------|
| pH                                         | 7.58 ± 0.11                  |
| Specific conductance (25°C)                | 305 ± 7 µmho/cm <sup>a</sup> |
| Total dissolved solids                     | 235 ± 5 mg/L                 |
| Total hardness (as CaCO <sub>3</sub> )     | 255 ± 35 mg/L                |
| Calcium hardness (as CaCO <sub>3</sub> )   | 185 ± 7 mg/L                 |
| Magnesium hardness (as CaCO <sub>3</sub> ) | 70 ± 42 mg/L                 |
| Chloride (as Cl <sup>-</sup> )             | 88 ± 18 mg/L                 |
| Turbidity                                  | 1.04 ± 0.12 NTU <sup>b</sup> |

Note: An average of three samples was taken at monthly intervals from April to July 1986.

<sup>a</sup>1 mho = 1 S.

<sup>b</sup>NTU, nephelometric turbidity units.

The total active chlorine concentration was determined in each case by amperometric titration (APHA 1985) using a CL Titrimeter 397 (Fisher Scientific Co., Pittsburgh, PA, USA). The solar UV-A intensity measurements, the experimental procedure, and data analysis were similar to those previously described. The measured parameters (see sample data sheet in Appendix 15) included local time, flow rate (litres per hour), solar UV-A intensity (watts per square metre), and TCR (milligrams per litre). Temperature was not recorded. Exposure time or residence time, fluence, and percentage chlorine remaining were calculated.

## Results

The experiment with the batch halosol system prepared the ground for the continuous-flow system. A total of 11 experiments was run on solar reactors IA and IB (21 April–1 July 1986). The closely related results of these experiments justified pooling the experimental data for statistical analysis and evaluation.

The photochemical decay rates and other relevant values were computed from equations 10 and 11 using mean values to minimize any bias introduced inadvertently. These equations are considered mathematically good approximations for the assumed uniform flow (plug flow) of the chlorinated water through the reactors. The solar exposure time ( $T$ ) calculated for each interval was also based on uniform, laminar flow. The obtained data (Appendices 16 and 17) provided sufficient variability for reliable and statistically significant results ( $p < 0.001$ ).

The photolysis curve of HOCl (Fig. 29), and possibly other species such as chlorine monoxide, represents the percentage of the remaining chlorine residual as a function of fluence. A mean photodechlorination rate ( $k$ ) of 0.238 m<sup>2</sup>/W h was calculated for initial chlorine concentrations ranging from 1.63 to 7.65 mg/L. The calculated fluences required to effect 90 and 99% reductions in the initial chlorine residual were found to be 9.65 and 19.30 W h/m<sup>2</sup>, respectively.

## Discussion

The fundamental concept of the halosol system for water disinfection is based on the use of a combined disinfection mode through the use of two or more

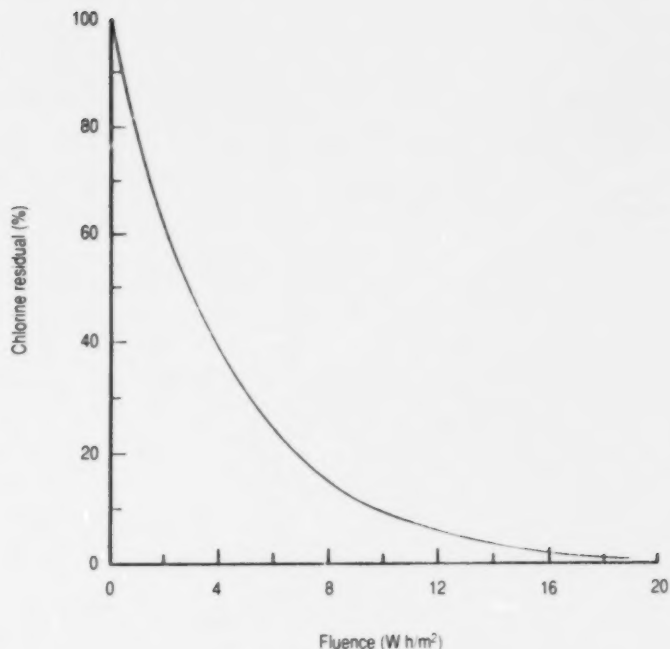


Fig. 29. Dechlorination (% of remaining chlorine residuals) as a function of solar UV-A fluence. Based on data from Appendix 16 and equation 9:  $R = 100e^{-0.238/I}$  ( $n = 12$ ,  $r = -0.985$ ,  $p < 0.001$ ).

cooperative biocidal agents: halogens (particularly chlorine) and solar radiation. This system enhances the biocidal action of the individual agents and widens their scope of effectiveness when combined.

Waterborne pathogenic bacteria are more efficiently destroyed by halogens (chlorine, iodine, and some of their derivatives) than are viruses, spores, ova, and protozoa. This shortcoming may lead to partial success when these disinfectants are applied to highly polluted waters in endemic areas. Sunlight has proven to have similar bactericidal properties (Chamberlin and Mitchell 1978; Mitchell and Chamberlin 1978; Harm 1980; Acra et al. 1980, 1984), but its action on viruses, ova, protozoa, and spores remains unclear. Nevertheless, combined effects of the two forms of disinfection (halosol process) could destroy highly resistant microorganisms and their latent stages. This hypothesis is not unfounded in view of the known germicidal effects of solar radiation and free chlorine residuals, and the possible involvement of highly reactive photochemical by-products such as singlet oxygen and chlorine monoxide. Whether or not a synergistic interaction takes place among these biocidal agents remains to be investigated.

During the haloform reaction, expected to occur between the natural bromides and the active chlorine residual in chlorinated water, the liberated hypobromite (HOBr) will help the harmful haloforms form. This has to be considered carefully. Solar radiation could inhibit this process by enhancing the photodecomposition of hypobromite. In addition, photosensitive organic pollutants, humates, and other

trihalomethane precursors present in water could be equally decomposed by photolysis.

Removing excess halogen residuals helps in alleviating consumer complaints. Photodechlorination could also be useful for chlorinated waters used in food-processing plants or for dechlorinating effluent before discharge.

Different physical and chemical water characteristics could affect the halosol process by influencing the performance of each disinfectant. Although the water used for the halosol experiments was taken from the same source as in other experiments, some of its characteristics had changed (Tables 2 and 5) as the fresh water supply is supplemented with saline groundwater during the dry season (Acra et al. 1985).

Temperature and pH influence reactions of halogens in water and the formation of active halogen residuals. These, in turn, would affect the inactivation of the waterborne organisms (Sconce 1962; Jolley et al. 1980; Cheremissinoff et al. 1981). Acidic waters and high temperatures are detrimental to many microorganisms and tend to enhance their inactivation by disinfectants (Berg 1978; Mitchell 1978; Gaudy and Gaudy 1980). The more active form of chlorine ( $\text{HOCl}$ ) predominates at pH below 7.53, whereas the weaker hypochlorite ion ( $\text{OCl}^-$ ) is the predominant species above this pH (Reinhard and Stumm 1980). Because the rise of temperature in the test water in the reactor could not have exceeded  $10^\circ\text{C}$ , the potential effect on the chlorine–water reaction and on the germicidal action of the active chlorine residual might be enhanced to some extent.

A mean turbidity level of 1.04 NTU is not sufficiently high to markedly retard transmission of sunlight through water in the solar reactor. In any case, suspended mineral sediments in water layers of  $\leq 25$  cm can still induce photolysis by scattered solar radiation (Miller and Zepp 1979).

Salts, heavy metals, and hardness of water could stress or inhibit bacteria and viruses; this issue remains partially unresolved. It appears that different microorganisms respond differently to variations in these factors (Iverson and Brinckman 1978; Katzenelson 1978; Kenner 1978; Mitchell and Chamberlin 1978; Le Chevallier and McFeters 1985). It is not evident, however, that the high hardness level of the experimental water could have affected the reported halosol results.

When carried out with small batches, the halosol process revealed the following:

- the reactive halogen species formed in water ( $\text{HOCl}$  and  $\text{HOI}$ ) are sufficiently photosensitive to allow their rather rapid photodegradation;
- the photoreaction is capable of occurring in quiescent water exposed to sunlight in transparent glass containers having mean diameters up to 20 cm; and
- the most effective photoreactive components of sunlight capable of penetrating through the glass and the water were those in the wavelength region of 310–400 nm, with the violet–blue light next in order of effectiveness (Figs 1 and 28).

The curves in Fig. 30 represent the calculated  $T_{90}$  and  $T_{99}$  values for photodechlorination at different wavelengths. Some of these observations have also

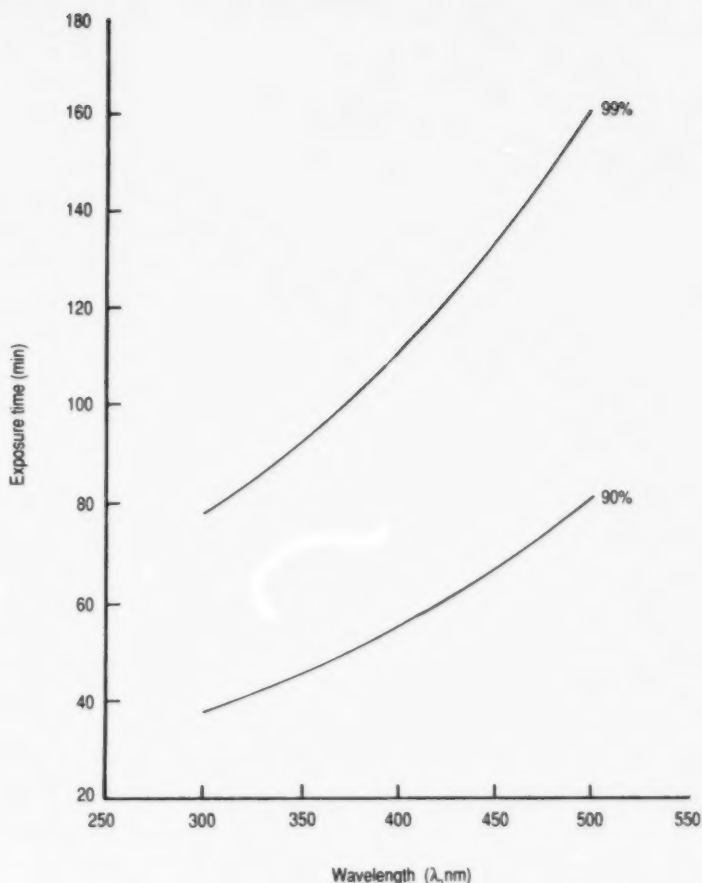


Fig. 30. Time required to remove 90 and 99% of the chlorine residual in water exposed to solar radiation in transparent glass containers as a function of wavelength.

$$T_{90} = 12.5e^{0.0041\lambda} \quad (n = 8, r = 0.785, p < 0.05); \quad T_{99} = 26.0e^{0.0041\lambda} \quad (n = 8, r = 0.783, p < 0.05).$$

been seen in the flow-through system, which produces equally satisfactory results under conditions where the halogenated water flows continuously through the solar reactor. The photodecay reactions in both cases are presumed to follow the same first-order pattern. Consequently, the percentage reduction in the chlorine residual is exponentially proportional to the product of solar intensity ( $I$ ) and exposure time ( $T$ ) (or residence time of water passing through the reactor). For a given percentage reduction in the concentration of chlorine residual, this relationship can be expressed as fluence ( $F = IT$ ).

As solar intensity increases, exposure time would have to be decreased proportionally to keep the product, or fluence, constant. In the flow-through system, this would have to be handled by regulating the rate of flow. The calculated  $T$  values based on the experimental data for different solar UV-A intensities and

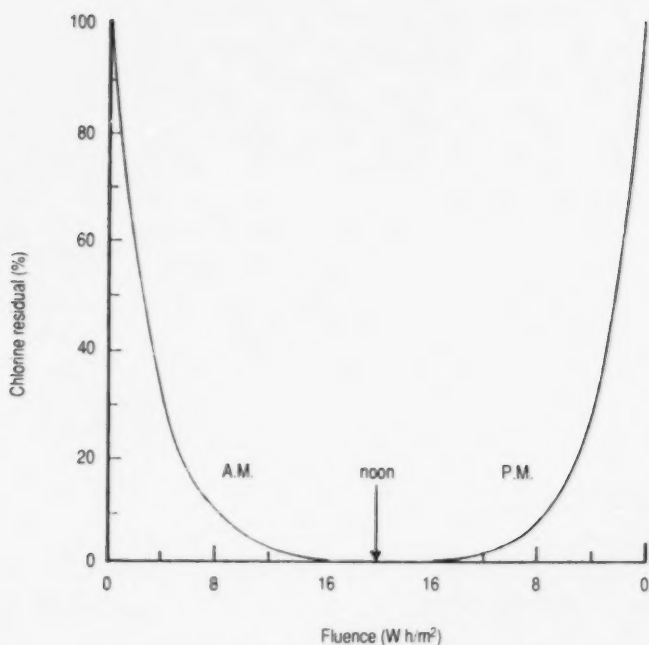


Fig. 31. Reduction in total chlorine residual as a function of solar UV-A fluence throughout the day.

percentages of remaining chlorine residuals (Appendix 18) will be useful in this regard. However, there could be difficulties in practice because the percentage reduction in chlorine residuals tends to vary with the time of day and, hence, with the prevailing solar intensity or fluence (Fig. 31). Suggestions for resolving this issue for the solar disinfection of drinking water using solar reactors are also applicable. It is expected that other halogens, particularly iodine and bromine, would display a pattern of response to solar radiation similar to that of chlorine.

## Conclusions and recommendations

The developed halosol process was tested on a pilot scale and has proven to be a functional and simple technique for water disinfection. With some refinements, field testing, and assessment of costs and acceptability, its application in developing countries with adequate sunlight and a high risk of waterborne diseases could become a reality. By replicating the solar reactor modules, it would be feasible to increase the capacity and productivity of the units. Installing a radiometric device to synchronize the water flow with the variable solar intensity is feasible and desirable.

Some areas needing research that emerged during this study are the following:

- outdoor swimming pools are likely to consume more chlorine or iodine than indoor pools because of increased losses induced by sunlight — of relevance

is the possibility of removal of halogen residuals from disinfected water in fish aquaria;

- similar precautions as those suggested for handling water samples for bacterial analysis (Fujioka and Narikawa 1982; Le Chevallier and McFeters 1985) have to be considered for halogen analysis;
- photodecomposition studies of other water disinfectants (interhalogens and hydrogen peroxide) may lead to practical applications;
- the proposed halosol system should be tested with treated sewage effluent used for irrigation, livestock watering, or hydroponic cultivation; and
- haloform reactions in chlorinated drinking water from coastal wells affected by seawater intrusion, with and without solar treatment, should be investigated.

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## Appendices

Appendix 1. Monthly solar UV-A intensities (mW/cm<sup>2</sup>) measured in Beirut on horizontal (H) and vertical (V) surfaces at noon (1985/86).

| Month | H                | V              | V/H              |
|-------|------------------|----------------|------------------|
| Feb.  | 600 ± 317 (18)   | 540 ± 184 (6)  | 0.80 ± 0.17 (6)  |
| Mar.  | 1 048 ± 375 (20) | 565 ± 240 (20) | 0.55 ± 0.15 (20) |
| Apr.  | 1 200 ± 525 (17) | 415 ± 160 (17) | 0.38 ± 0.13 (17) |
| May   | 1 355 ± 558 (21) | 280 ± 71 (21)  | 0.25 ± 0.10 (21) |
| June  | 1 820 ± 160 (14) | 275 ± 64 (14)  | 0.15 ± 0.04 (14) |
| July  | 1 685 ± 315 (20) | 285 ± 43 (20)  | 0.18 ± 0.08 (20) |
| Aug.  | 1 365 ± 295 (14) | 405 ± 155 (14) | 0.30 ± 0.12 (14) |
| Sept. | 1 300 ± 237 (17) | 425 ± 75 (17)  | 0.33 ± 0.07 (17) |
| Oct.  | 908 ± 262 (22)   | 600 ± 208 (22) | 0.66 ± 0.16 (22) |
| Nov.  | 605 ± 299 (20)   | 550 ± 298 (20) | 0.89 ± 0.26 (20) |
| Dec.  | 479 ± 265 (20)   | 580 ± 395 (20) | 1.05 ± 0.39 (20) |
| Jan.  | 599 ± 279 (21)   | 630 ± 370 (21) | 0.97 ± 0.25 (21) |
| Feb.  | 900 ± 362 (20)   | 706 ± 308 (20) | 0.76 ± 0.14 (20) |

Note: Values are means ± standard deviations with the number of samples in parentheses.

Appendix 2. Seasonal distribution for solar UV-A intensity (mW/cm<sup>2</sup>) as measured in Beirut on horizontal (H) and vertical (V) surfaces under prevailing sky conditions.

| Season <sup>a</sup> | H           | V         | V/H           |
|---------------------|-------------|-----------|---------------|
| Spring (53)         | 1 329 ± 547 | 348 ± 167 | 0.308 ± 0.160 |
| Summer (52)         | 1 525 ± 340 | 348 ± 112 | 0.245 ± 0.110 |
| Autumn (59)         | 745 ± 327   | 592 ± 275 | 0.827 ± 0.323 |
| Winter (48)         | 690 ± 370   | 627 ± 360 | 0.870 ± 0.263 |
| Annual (212)        | 1 070 ± 540 | 480 ± 277 | 0.562 ± 0.368 |

Note: Values are means ± standard deviations.

<sup>a</sup>Spring, 21 March to 20 June 1985; summer, 21 June to 22 September 1985; autumn, 23 September to 21 December 1985; winter, 22 December 1985 to 28 February 1986; annual, 21 March 1985 to 28 February 1986. The number of observations is given in parentheses.

Appendix 3. Mean solar UV-A radiation incident on a horizontal surface measured on 3 consecutive days (7-9 October 1983) in Beirut (34° N) under clear-sky conditions.

| Time of day | Intensity (mW/cm <sup>2</sup> ) | Time of day | Intensity (mW/cm <sup>2</sup> ) |
|-------------|---------------------------------|-------------|---------------------------------|
| 0835        | 500                             | 1225        | 1 050                           |
| 0845        | 555                             | 1235        | 985                             |
| 0855        | 615                             | 1245        | 955                             |
| 0905        | 660                             | 1255        | 915                             |
| 0915        | 705                             | 1305        | 875                             |
| 0925        | 745                             | 1315        | 840                             |
| 0935        | 790                             | 1325        | 780                             |
| 0945        | 850                             | 1335        | 760                             |
| 0955        | 910                             | 1345        | 710                             |
| 1005        | 960                             | 1355        | 665                             |
| 1015        | 990                             | 1405        | 625                             |
| 1025        | 1 025                           | 1415        | 565                             |
| 1035        | 1 060                           | 1425        | 515                             |
| 1045        | 1 075                           | 1435        | 455                             |
| 1055        | 1 095                           | 1445        | 415                             |
| 1105        | 1 095                           | 1455        | 365                             |
| 1115        | 1 100                           | 1505        | 310                             |
| 1125        | 1 085                           | 1515        | 280                             |
| 1135        | 1 095                           | 1525        | 130                             |
| 1145        | 1 105                           | 1535        | 110                             |
| 1155        | 1 095                           | 1545        | 90                              |
| 1205        | 1 195                           | 1555        | 70                              |
| 1215        | 1 085                           |             |                                 |

Appendix 4. Solar UV-A intensity ( $\text{mW}/\text{cm}^2$ ) on horizontal (H) and vertical (V) surfaces measured in Beirut under hazy-sky conditions (2 June 1985).

| Time of day | H     | V   | V/H  |
|-------------|-------|-----|------|
| 0830        | 620   | 760 | 1.23 |
| 0845        | 710   | 890 | 1.25 |
| 0900        | 720   | 710 | 0.99 |
| 0915        | 850   | 800 | 0.94 |
| 0930        | 970   | 790 | 0.81 |
| 0945        | 1 015 | 680 | 0.67 |
| 1000        | 1 075 | 750 | 0.70 |
| 1015        | 1 100 | 380 | 0.36 |
| 1030        | 1 080 | 430 | 0.40 |
| 1045        | 1 200 | 250 | 0.21 |
| 1100        | 1 440 | 370 | 0.26 |
| 1200        | 1 970 | 190 | 0.10 |
| 1230        | 1 580 | 190 | 0.12 |
| 1345        | 1 750 | 220 | 0.13 |
| 1415        | 1 280 | 370 | 0.29 |
| 1430        | 1 270 | 380 | 0.30 |
| 1445        | 1 160 | 220 | 0.19 |
| 1500        | 1 240 | 590 | 0.48 |
| 1515        | 780   | 280 | 0.36 |
| 1530        | 850   | 430 | 0.51 |
| 1545        | 720   | 500 | 0.69 |
| 1600        | 510   | 500 | 0.98 |
| 1615        | 450   | 470 | 1.04 |
| 1630        | 330   | 340 | 1.03 |

Appendix 5. Solar UV-A intensity ( $\text{W}/\text{m}^2$ ) relative to the global radiation ( $G$ ) incident on inclined ( $35^\circ$ ) south-facing surfaces in Beirut under overcast- (21 April 1985) and clear-sky (24 April 1985) conditions.

| Time of day | Overcast  |          |               | Time of day | Clear     |           |               |
|-------------|-----------|----------|---------------|-------------|-----------|-----------|---------------|
|             | UV-A      | $G$      | UV-A/ $G$ (%) |             | UV-A      | $G$       | UV-A/ $G$ (%) |
| 0943        | 6.2       | 120      | 5.17          | 0848        | 13.7      | 215       | 6.37          |
| 1028        | 6.9       | 130      | 5.31          | 0916        | 16.6      | 300       | 5.53          |
| 1047        | 7.1       | 140      | 5.71          | 0930        | 17.8      | 340       | 5.24          |
| 1122        | 6.9       | 145      | 4.76          | 0951        | 19.8      | 430       | 4.60          |
| 1149        | 5.5       | 110      | 5.00          | 1000        | 20.9      | 440       | 4.75          |
| 1218        | 5.1       | 105      | 4.86          | 1019        | 21.5      | 580       | 3.71          |
| 1252        | 5.2       | 95       | 5.47          | 1045        | 23.0      | 680       | 3.38          |
| 1319        | 4.3       | 85       | 5.06          | 1055        | 23.4      | 680       | 3.44          |
| 1330        | 9.7       | 165      | 5.88          | 1107        | 23.8      | 700       | 3.40          |
| 1351        | 5.9       | 115      | 5.13          | 1119        | 23.8      | 710       | 3.35          |
| Mean        | 6.3       | 125      | 5.24          | Mean        | 20.4      | 508       | 4.38          |
| $\pm$ SD    | $\pm 1.5$ | $\pm 27$ | $\pm 0.36$    | $\pm$ SD    | $\pm 3.4$ | $\pm 186$ | $\pm 1.08$    |

Appendix 6. Sample of a data sheet used for the experiments on solar disinfection of contaminated water exposed in a continuous-flow system.

|                                                                          |                        |                                         |                     |                 |                               |                               |                           |          |                        |          |      |
|--------------------------------------------------------------------------|------------------------|-----------------------------------------|---------------------|-----------------|-------------------------------|-------------------------------|---------------------------|----------|------------------------|----------|------|
| Experiment No. <u>7</u>                                                  |                        | Solar Reactor: <u>IA</u>                |                     |                 |                               |                               |                           |          |                        |          |      |
| Date: <u>13 Aug. 1986</u>                                                |                        |                                         |                     |                 |                               |                               |                           |          |                        |          |      |
| Sky conditions: clear <u>hazy</u> partly cloudy <u>x</u> cloudy <u>—</u> |                        |                                         |                     |                 |                               |                               |                           |          |                        |          |      |
| Contaminant added: sewage (%) <u>0.2</u> bacterial culture <u>—</u>      |                        |                                         |                     |                 |                               |                               |                           |          |                        |          |      |
| Bacteria tested: <u>Coliforms</u>                                        |                        |                                         |                     |                 |                               |                               |                           |          |                        |          |      |
| Culture medium: <u>Desoxychol, Lactose Agar</u>                          |                        | Manufacturer: <u>Difco Laboratories</u> |                     |                 |                               |                               |                           |          |                        |          |      |
| Incubation: temperature <u>35.5 (°C)</u>                                 |                        | period <u>24 (h)</u>                    |                     |                 |                               |                               |                           |          |                        |          |      |
| Time of day                                                              | Solar UV-A             |                                         |                     |                 |                               |                               |                           |          |                        |          |      |
|                                                                          | Water temperature (°C) |                                         | Exposure time (min) | Flow rate (L/h) | Intensity (W/m <sup>2</sup> ) | Fluence (W h/m <sup>2</sup> ) | Bacterial counts (CFU/mL) |          | Bacterial survival (%) |          |      |
|                                                                          | Influent               | Effluent                                |                     |                 |                               |                               | Mean                      | Influent |                        | Effluent |      |
|                                                                          | 1015                   | 32.0                                    | 34.0                | 33.0            | 26                            | 11.23                         | 11.23                     | 4.87     | 2 150                  | 445      | 20.7 |
|                                                                          | 1040                   | 33.0                                    | 35.5                | 34.2            | 26                            | 11.23                         | 12.93                     | 5.60     | 1 715                  | 285      | 16.6 |
|                                                                          | 1100                   | 34.0                                    | 36.0                | 35.0            | 26                            | 11.23                         | 15.55                     | 6.74     | 1 740                  | 80       | 4.6  |
|                                                                          | 1130                   | 34.0                                    | 36.5                | 35.2            | 26                            | 11.23                         | 17.80                     | 7.71     | 1 020                  | 135      | 13.2 |
|                                                                          | 1200                   | 35.0                                    | 37.0                | 36.0            | 26                            | 11.23                         | 19.35                     | 8.39     | 280                    | 40       | 14.3 |
|                                                                          | 1230                   | 36.0                                    | 37.5                | 36.8            | 26                            | 11.23                         | 19.55                     | 8.47     | 340                    | 40       | 11.8 |
|                                                                          | 1300                   | 37.0                                    | 39.0                | 38.0            | 26                            | 11.23                         | 19.55                     | 8.47     | 65                     | 6        | 9.2  |
|                                                                          | Mean ± SD*             | 34.4                                    | 36.5                | 35.5            | 26                            | 11.23                         | 16.57                     | 7.20     | 1 045                  | 147      | 12.9 |
|                                                                          |                        | ±1.7                                    | ±1.6                | ±1.7            | ±0                            | ±0.00                         | ±3.40                     | ±1.50    | ±835                   | ±160     | ±8.2 |

\*SD, standard deviation.

Appendix 7. Summary of experimental mean values for solar inactivation of coliforms in contaminated water using solar reactor 1A (reactor 1B was used for experiment 24).

| Exp. No. | Date (1986) | Water temperature (°C) |          |      |                     | Flow rate (L/h) | Solar UV-A                    |                               | Bacterial counts (CFU/mL) |          | Bacterial survival (%) |
|----------|-------------|------------------------|----------|------|---------------------|-----------------|-------------------------------|-------------------------------|---------------------------|----------|------------------------|
|          |             | Influent               | Effluent | Mean | Exposure time (min) |                 | Intensity (W/m <sup>2</sup> ) | Fluence (W h/m <sup>2</sup> ) | Influent                  | Effluent |                        |
|          |             |                        |          |      |                     |                 |                               |                               |                           |          |                        |
| 7        | 13 Aug.     | 34.4                   | 36.5     | 35.5 | 11.2                | 26              | 16.6                          | 7.2                           | 1 045                     | 145      | 12.9                   |
| 10       | 28 Aug.     | 32.3                   | 35.4     | 33.8 | 10.4                | 28              | 13.9                          | 6.6                           | 325                       | 20       | 2.2                    |
| 11       | 4 Sept.     | 33.2                   | 38.1     | 35.7 | 7.8                 | 38              | 15.9                          | 10.0                          | 475                       | 45       | 9.0                    |
| 12       | 9 Sept.     | 34.6                   | 39.1     | 36.8 | 6.5                 | 45              | 19.0                          | 14.3                          | 335                       | 15       | 9.1                    |
| 13       | 11 Sept.    | 35.9                   | 38.1     | 37.0 | 4.4                 | 66              | 16.3                          | 18.0                          | 255                       | 0.5      | 0.1                    |
| 14       | 17 Sept.    | 38.0                   | 40.6     | 39.3 | 4.6                 | 63              | 15.7                          | 16.5                          | 205                       | 5        | 1.5                    |
| 15       | 23 Sept.    | 36.7                   | 41.4     | 39.0 | 6.6                 | 44              | 18.5                          | 13.6                          | 185                       | 15       | 9.6                    |
| 21       | 5 Nov.      | 25.8                   | 29.5     | 27.6 | 37.1                | 8               | 15.9                          | 2.1                           | 2 275                     | 965      | 36.9                   |
| 22       | 12 Nov.     | 24.9                   | 29.4     | 27.2 | 8.9                 | 33              | 13.3                          | 7.3                           | 1 105                     | 290      | 15.9                   |
| 23       | 19 Nov.     | 25.8                   | 33.6     | 29.7 | 5.6                 | 53              | 13.8                          | 12.1                          | 940                       | 30       | 1.9                    |
| 24       | 27 Nov.     | 28.6                   | 30.1     | 29.4 | 10.5                | 30              | 12.2                          | 6.1                           | 255                       | 75       | 19.6                   |

Appendix 8. Summary of experimental mean values for solar inactivation of *Streptococcus faecalis* in contaminated water using solar reactor 1A (reactor 1B was used for experiment 24).

| Exp. No. | Date (1986) | Water temperature (°C) |          |      |                     | Flow rate (L/h) | Solar UV A                    |                               | Bacterial counts (CFU/mL) |          | Bacterial survival (%) |
|----------|-------------|------------------------|----------|------|---------------------|-----------------|-------------------------------|-------------------------------|---------------------------|----------|------------------------|
|          |             | Influent               | Effluent | Mean | Exposure time (min) |                 | Intensity (W/m <sup>2</sup> ) | Fluence (W h/m <sup>2</sup> ) | Influent                  | Effluent |                        |
|          |             |                        |          |      |                     |                 |                               |                               |                           |          |                        |
|          |             |                        |          |      |                     |                 |                               |                               |                           |          |                        |
| 7        | 13 Aug.     | 34.4                   | 36.5     | 35.5 | 11.2                | 26              | 16.6                          | 7.2                           | 490                       | 205      | 38.6                   |
| 10       | 28 Aug.     | 32.3                   | 35.4     | 33.8 | 10.4                | 28              | 13.9                          | 6.6                           | 576                       | 150      | 23.4                   |
| 11       | 4 Sept.     | 33.2                   | 38.1     | 35.7 | 7.8                 | 38              | 15.9                          | 10.0                          | 445                       | 55       | 13.6                   |
| 12       | 9 Sept.     | 34.6                   | 39.1     | 36.8 | 6.5                 | 45              | 19.0                          | 14.3                          | 195                       | 15       | 7.9                    |
| 13       | 11 Sept.    | 35.9                   | 38.1     | 37.0 | 4.4                 | 66              | 16.3                          | 18.0                          | 255                       | 0.5      | 0.1                    |
| 14       | 17 Sept.    | 38.0                   | 40.6     | 39.3 | 4.6                 | 63              | 15.7                          | 16.5                          | 290                       | 1.7      | 0.5                    |
| 15       | 23 Sept.    | 36.7                   | 41.4     | 39.0 | 6.6                 | 44              | 18.5                          | 13.6                          | 265                       | 20       | 8.9                    |
| 17       | 7 Oct.      | 33.1                   | 37.8     | 35.5 | 17.2                | 17              | 15.0                          | 4.2                           | 75                        | 15       | 22.1                   |
| 21       | 5 Nov.      | 25.8                   | 29.5     | 27.6 | 37.1                | 8               | 15.9                          | 2.1                           | 375                       | 220      | 59.1                   |
| 23       | 19 Nov.     | 25.8                   | 33.6     | 29.7 | 5.6                 | 53              | 13.8                          | 12.1                          | 495                       | 55       | 9.3                    |
| 24       | 27 Nov.     | 28.6                   | 30.1     | 29.4 | 10.5                | 30              | 12.2                          | 6.1                           | 210                       | 45       | 18.4                   |

Appendix 9. Summary of experimental mean values for solar inactivation of *Escherichia coli* in contaminated water using solar reactor 1A (reactor 1B was used for experiments 25 and 26).

| Exp. No. | Date (1986) | Solar UV A             |          |      |                     |                 |                               |                               |                           |          |                        |  |  |  |  |
|----------|-------------|------------------------|----------|------|---------------------|-----------------|-------------------------------|-------------------------------|---------------------------|----------|------------------------|--|--|--|--|
|          |             | Water temperature (°C) |          |      | Exposure time (min) | Flow rate (L/h) | Intensity (W/m <sup>2</sup> ) | Fluence (W h/m <sup>2</sup> ) | Bacterial counts (CFU/mL) |          | Bacterial survival (%) |  |  |  |  |
|          |             | Influent               | Effluent | Mean |                     |                 |                               |                               | Influent                  | Effluent |                        |  |  |  |  |
|          |             |                        |          |      |                     |                 |                               |                               |                           |          |                        |  |  |  |  |
| 16       | 30 Sept.    | 35.9                   | 39.4     | 37.7 | 29                  | 10.2            | 14.9                          | 7.3                           | 2 710                     | 115      | 5.0                    |  |  |  |  |
| 18       | 15 Oct.     | 30.4                   | 34.8     | 32.6 | 16                  | 18.6            | 12.5                          | 3.3                           | 4 340                     | 2 230    | 32.7                   |  |  |  |  |
| 19       | 21 Oct.     | 32.1                   | 36.6     | 34.4 | 68                  | 4.3             | 13.5                          | 15.3                          | 4 420                     | 10       | 0.2                    |  |  |  |  |
| 20       | 28 Oct.     | 32.6                   | 37.1     | 34.8 | 25                  | 11.4            | 12.4                          | 5.2                           | 5 720                     | 2 110    | 17.6                   |  |  |  |  |
| 25       | 3 Dec.      | 22.4                   | 25.9     | 24.1 | 29                  | 10.7            | 14.1                          | 6.8                           | 3 450                     | 820      | 16.2                   |  |  |  |  |
| 26       | 9 Dec.      | 23.0                   | 25.2     | 23.7 | 47                  | 6.6             | 10.2                          | 8.0                           | 3 670                     | 500      | 14.2                   |  |  |  |  |

Appendix 10. Summary of experimental mean values for solar inactivation of coliforms and *Streptococcus faecalis* in contaminated water using solar reactors IIA and IIB.

| Exp. No.                                         | Date (1986/87) | Water temperature (°C) |          |      |                 | Solar UV-A          |                               |                               |          |          | Bacterial counts (CFU/mL) |  | Bacterial survival (%) |
|--------------------------------------------------|----------------|------------------------|----------|------|-----------------|---------------------|-------------------------------|-------------------------------|----------|----------|---------------------------|--|------------------------|
|                                                  |                | Influent               | Effluent | Mean | Flow rate (L/h) | Exposure time (min) | Intensity (W/m <sup>2</sup> ) | Fluence (W h/m <sup>2</sup> ) | Influent | Effluent |                           |  |                        |
|                                                  |                |                        |          |      |                 |                     |                               |                               |          |          |                           |  |                        |
|                                                  |                |                        |          |      |                 |                     |                               |                               |          |          |                           |  |                        |
| Solar reactor IIA: Coliforms                     |                |                        |          |      |                 |                     |                               |                               |          |          |                           |  |                        |
| 27                                               | 18 Dec.        | 22.4                   | 21.6     | 22.0 | 8.1             | 64                  | 9.4                           | 10.0                          | 580      | 40       | 4.2                       |  |                        |
| 28                                               | 23 Dec.        | 24.6                   | 24.9     | 24.7 | 16.3            | 35                  | 12.1                          | 7.1                           | 755      | 145      | 13.3                      |  |                        |
| Solar reactor IIA: <i>Streptococcus faecalis</i> |                |                        |          |      |                 |                     |                               |                               |          |          |                           |  |                        |
| 27                                               | 18 Dec.        | 22.4                   | 21.6     | 22.0 | 8.9             | 64                  | 9.4                           | 10.0                          | 285      | 35       | 17.0                      |  |                        |
| Solar reactor IIB: Coliforms                     |                |                        |          |      |                 |                     |                               |                               |          |          |                           |  |                        |
| 29                                               | 13 Jan.        | 24.9                   | 24.3     | 24.5 | 16.9            | 64                  | 11.4                          | 12.1                          | 75       | 5        | 2.9                       |  |                        |
| 30                                               | 22 Jan.        | 20.6                   | 20.3     | 20.4 | 20.3            | 53                  | 3.3                           | 2.9                           | 180      | 35       | 12.2                      |  |                        |

Appendix 11. Analysis of variance for the percentage survival of test bacteria against solar UV-A fluence.

| Source of variation <sup>a</sup> | Coliforms  |       |             | <i>S. faecalis</i> |       |          | <i>E. coli</i> |       |          |
|----------------------------------|------------|-------|-------------|--------------------|-------|----------|----------------|-------|----------|
|                                  | Regression |       | Residual    | Regression         |       | Residual | Regression     |       | Residual |
|                                  | 1          | SS    |             | 1                  | SS    |          | 1              | SS    |          |
| SS                               | 1          | 356.2 | 86.6        | 1                  | 264.9 | 395.1    | 1              | 489.5 | 40.0     |
| MS                               |            | 678.1 | 12.4        |                    | 324.9 | 49.4     |                | 489.5 | 13.3     |
| df                               |            | 2     | 7           |                    | 2     | 8        |                | 1     | 3        |
| F                                |            | 54.82 |             |                    | 26.83 |          |                | 36.69 |          |
|                                  |            |       | $p < 0.001$ |                    |       |          | $p < 0.001$    |       |          |

<sup>a</sup>SS, sum of squares; MS, mean square; df, degrees of freedom.

Appendix 12. Calculated values for sunlight exposure time (min) at specified solar UV-A intensities as a function of survival of coliform bacteria.

| Bacterial survival (%) | Solar UV-A intensity (W/m <sup>2</sup> ) |     |     |     |      |      |      |      |      |      |      |      |
|------------------------|------------------------------------------|-----|-----|-----|------|------|------|------|------|------|------|------|
|                        | 2.0                                      | 4.0 | 6.0 | 8.0 | 10.0 | 12.0 | 14.0 | 16.0 | 18.0 | 20.0 | 22.0 | 24.0 |
| 95                     | 5.7                                      | 2.9 | 1.9 | 1.4 | 1.1  | 1.0  | 0.8  | 0.7  | 0.6  | 0.6  | 0.5  | 0.5  |
| 90                     | 11                                       | 5.7 | 3.8 | 2.9 | 2.3  | 1.9  | 1.6  | 1.4  | 1.3  | 1.1  | 1.0  | 1.0  |
| 85                     | 18                                       | 8.9 | 5.9 | 4.4 | 3.5  | 3.0  | 2.5  | 2.2  | 2.0  | 1.8  | 1.6  | 1.5  |
| 80                     | 24                                       | 12  | 8.0 | 6.0 | 4.8  | 4.0  | 3.4  | 2.0  | 2.7  | 2.4  | 2.2  | 2.0  |
| 75                     | 31                                       | 16  | 10  | 7.8 | 6.2  | 5.2  | 4.4  | 3.9  | 3.5  | 3.1  | 2.8  | 2.6  |
| 70                     | 38                                       | 19  | 13  | 9.6 | 7.7  | 6.4  | 5.5  | 4.8  | 4.3  | 3.8  | 3.5  | 3.2  |
| 65                     | 46                                       | 23  | 15  | 12  | 9.3  | 7.8  | 6.6  | 5.8  | 5.2  | 4.6  | 4.2  | 3.9  |
| 60                     | 55                                       | 27  | 18  | 14  | 11   | 9.2  | 7.7  | 6.9  | 6.1  | 5.5  | 5.0  | 4.6  |
| 55                     | 64                                       | 32  | 22  | 16  | 13   | 11   | 9.2  | 8.1  | 7.2  | 6.4  | 5.9  | 5.4  |
| 50                     | 75                                       | 37  | 25  | 19  | 15   | 12   | 11   | 9.3  | 8.3  | 7.5  | 6.8  | 6.2  |
| 45                     | 86                                       | 43  | 29  | 21  | 17   | 14   | 12   | 11   | 9.5  | 8.6  | 7.8  | 7.2  |
| 40                     | 99                                       | 49  | 33  | 25  | 20   | 16   | 14   | 12   | 11   | 9.9  | 9.0  | 8.2  |
| 35                     | 113                                      | 57  | 38  | 28  | 23   | 19   | 16   | 14   | 13   | 11   | 10   | 9.4  |
| 30                     | 130                                      | 65  | 43  | 32  | 26   | 22   | 19   | 16   | 14   | 13   | 12   | 11   |
| 25                     | 149                                      | 75  | 50  | 37  | 30   | 25   | 21   | 19   | 17   | 15   | 14   | 12   |
| 20                     | 173                                      | 87  | 58  | 43  | 35   | 29   | 25   | 22   | 19   | 17   | 16   | 14   |
| 15                     | 204                                      | 105 | 68  | 51  | 41   | 34   | 29   | 26   | 23   | 20   | 18   | 17   |
| 10                     | 248                                      | 124 | 82  | 62  | 50   | 41   | 35   | 31   | 28   | 25   | 22   | 21   |
| 9                      | 259                                      | 129 | 86  | 65  | 52   | 43   | 37   | 32   | 29   | 26   | 24   | 22   |
| 8                      | 272                                      | 136 | 90  | 68  | 54   | 45   | 39   | 34   | 30   | 27   | 25   | 23   |
| 7                      | 286                                      | 143 | 95  | 71  | 57   | 48   | 41   | 36   | 32   | 29   | 26   | 24   |
| 6                      | 302                                      | 151 | 101 | 76  | 60   | 50   | 43   | 38   | 34   | 30   | 27   | 25   |
| 5                      | 322                                      | 161 | 107 | 80  | 64   | 54   | 46   | 40   | 36   | 32   | 29   | 27   |
| 4                      | 346                                      | 173 | 115 | 86  | 69   | 58   | 49   | 43   | 38   | 35   | 31   | 29   |
| 3                      | 377                                      | 188 | 126 | 94  | 75   | 63   | 54   | 47   | 42   | 38   | 34   | 31   |
| 2                      | 421                                      | 210 | 140 | 105 | 84   | 70   | 60   | 53   | 47   | 42   | 38   | 35   |
| 1                      | 495                                      | 248 | 165 | 124 | 99   | 82   | 71   | 62   | 55   | 50   | 45   | 41   |
| 0.5                    | 569                                      | 285 | 190 | 142 | 114  | 95   | 81   | 71   | 63   | 57   | 52   | 47   |
| 0.1                    | 742                                      | 371 | 248 | 186 | 148  | 124  | 106  | 93   | 82   | 74   | 68   | 62   |
| 0.01                   | 990                                      | 495 | 330 | 247 | 198  | 165  | 141  | 124  | 110  | 99   | 90   | 82   |

Note: Data were obtained using equation 3 and mean experimental values.

Appendix 13. Calculated values for sunlight exposure time (min) at specified solar UV-A intensities as a function of survival of *Streptococcus faecalis*.

| Bacterial survival (%) | Solar UV-A intensity (W/m <sup>2</sup> ) |     |     |     |      |      |      |      |      |      |      |      |
|------------------------|------------------------------------------|-----|-----|-----|------|------|------|------|------|------|------|------|
|                        | 2.0                                      | 4.0 | 6.0 | 8.0 | 10.0 | 12.0 | 14.0 | 16.0 | 18.0 | 20.0 | 22.0 | 24.0 |
| 95                     | 6.0                                      | 3.0 | 2.0 | 1.5 | 1.2  | 1.0  | 0.9  | 0.8  | 0.7  | 0.6  | 0.5  | 0.5  |
| 90                     | 12                                       | 6.2 | 4.1 | 3.1 | 2.5  | 2.0  | 1.8  | 1.5  | 1.4  | 1.2  | 1.1  | 1.0  |
| 85                     | 19                                       | 9.4 | 6.3 | 4.7 | 3.8  | 3.2  | 2.7  | 2.4  | 2.9  | 1.9  | 1.7  | 1.6  |
| 80                     | 26                                       | 13  | 8.7 | 6.5 | 5.2  | 4.4  | 3.7  | 3.3  | 2.9  | 2.6  | 2.4  | 2.2  |
| 75                     | 34                                       | 17  | 11  | 8.4 | 6.7  | 5.6  | 4.8  | 4.2  | 3.7  | 3.4  | 3.0  | 2.8  |
| 70                     | 41                                       | 21  | 14  | 10  | 8.3  | 6.9  | 5.9  | 5.2  | 4.6  | 4.1  | 3.8  | 3.4  |
| 65                     | 50                                       | 25  | 17  | 12  | 10   | 8.4  | 7.2  | 6.3  | 5.6  | 5.0  | 4.6  | 4.2  |
| 60                     | 59                                       | 30  | 20  | 15  | 12   | 9.9  | 8.5  | 7.4  | 6.6  | 5.9  | 5.4  | 5.0  |
| 55                     | 70                                       | 35  | 23  | 17  | 14   | 12   | 9.9  | 8.7  | 7.7  | 7.0  | 6.3  | 5.8  |
| 50                     | 81                                       | 40  | 27  | 20  | 16   | 13   | 12   | 10   | 9.0  | 8.1  | 7.3  | 6.7  |
| 45                     | 93                                       | 46  | 31  | 23  | 18   | 15   | 13   | 12   | 10   | 9.3  | 8.4  | 7.7  |
| 40                     | 106                                      | 53  | 35  | 27  | 22   | 18   | 15   | 13   | 12   | 11   | 9.7  | 8.9  |
| 35                     | 122                                      | 61  | 41  | 30  | 24   | 20   | 17   | 15   | 14   | 12   | 11   | 10   |
| 30                     | 140                                      | 70  | 47  | 35  | 28   | 23   | 20   | 18   | 16   | 14   | 13   | 12   |
| 25                     | 161                                      | 81  | 54  | 40  | 32   | 27   | 23   | 20   | 18   | 16   | 15   | 13   |
| 20                     | 187                                      | 93  | 62  | 47  | 37   | 31   | 27   | 23   | 21   | 19   | 17   | 16   |
| 15                     | 220                                      | 110 | 73  | 55  | 44   | 37   | 31   | 28   | 24   | 22   | 20   | 18   |
| 10                     | 267                                      | 134 | 89  | 67  | 54   | 45   | 38   | 33   | 30   | 27   | 24   | 22   |
| 9                      | 280                                      | 140 | 93  | 70  | 56   | 47   | 40   | 35   | 31   | 28   | 25   | 23   |
| 8                      | 293                                      | 147 | 98  | 73  | 59   | 49   | 42   | 37   | 33   | 29   | 27   | 24   |
| 7                      | 309                                      | 154 | 103 | 77  | 62   | 51   | 44   | 39   | 34   | 31   | 28   | 26   |
| 6                      | 326                                      | 163 | 109 | 82  | 65   | 54   | 47   | 41   | 36   | 33   | 30   | 27   |
| 5                      | 348                                      | 174 | 116 | 87  | 70   | 58   | 50   | 43   | 39   | 35   | 32   | 29   |
| 4                      | 374                                      | 187 | 124 | 93  | 75   | 62   | 53   | 47   | 42   | 37   | 34   | 31   |
| 3                      | 407                                      | 203 | 136 | 102 | 81   | 68   | 58   | 51   | 45   | 41   | 37   | 34   |
| 2                      | 454                                      | 227 | 151 | 114 | 91   | 76   | 65   | 57   | 50   | 45   | 41   | 38   |
| 1                      | 534                                      | 267 | 178 | 134 | 107  | 89   | 76   | 66   | 59   | 53   | 49   | 44   |
| 0.5                    | 615                                      | 308 | 205 | 154 | 123  | 102  | 88   | 77   | 68   | 62   | 56   | 51   |
| 0.1                    | 802                                      | 401 | 267 | 200 | 160  | 134  | 114  | 100  | 89   | 80   | 73   | 67   |
| 0.01                   | 1 069                                    | 534 | 356 | 267 | 214  | 178  | 153  | 13   | 119  | 107  | 97   | 89   |

Note: Data were obtained using equation 3 and mean experimental values.

Appendix 14. Calculated values for sunlight exposure time (min) at specified solar UV-A intensities as a function of survival of *Escherichia coli*.

| Bacterial survival (%) | Solar UV-A intensity (W/m <sup>2</sup> ) |     |     |     |      |      |      |      |      |      |      |      |
|------------------------|------------------------------------------|-----|-----|-----|------|------|------|------|------|------|------|------|
|                        | 2.0                                      | 4.0 | 6.0 | 8.0 | 10.0 | 12.0 | 14.0 | 16.0 | 18.0 | 20.0 | 22.0 | 24.0 |
| 95                     | 4.5                                      | 2.2 | 1.5 | 1.1 | 0.9  | 0.8  | 0.6  | 0.6  | 0.5  | 0.6  | 0.4  | 0.4  |
| 90                     | 8.7                                      | 4.4 | 2.9 | 2.2 | 1.7  | 1.4  | 1.2  | 1.1  | 1.0  | 0.9  | 0.8  | 0.8  |
| 85                     | 14                                       | 6.8 | 4.5 | 3.4 | 2.7  | 2.2  | 1.9  | 1.7  | 1.5  | 1.4  | 1.2  | 1.2  |
| 80                     | 19                                       | 9.3 | 6.2 | 4.6 | 3.7  | 3.1  | 2.7  | 2.3  | 2.1  | 1.9  | 1.7  | 1.6  |
| 75                     | 24                                       | 12  | 8.0 | 6.0 | 4.8  | 4.0  | 3.4  | 3.0  | 2.7  | 2.4  | 2.2  | 2.1  |
| 70                     | 30                                       | 15  | 9.9 | 7.4 | 5.9  | 5.0  | 4.2  | 3.7  | 3.3  | 3.0  | 2.7  | 2.6  |
| 65                     | 36                                       | 18  | 12  | 8.9 | 7.1  | 6.0  | 5.1  | 4.5  | 4.0  | 3.6  | 3.2  | 3.1  |
| 60                     | 42                                       | 21  | 14  | 11  | 8.5  | 7.0  | 6.0  | 5.3  | 4.7  | 4.2  | 3.8  | 3.7  |
| 55                     | 50                                       | 25  | 16  | 12  | 9.9  | 8.2  | 7.1  | 6.2  | 5.5  | 5.0  | 4.5  | 4.3  |
| 50                     | 58                                       | 29  | 19  | 14  | 12   | 9.6  | 8.2  | 7.2  | 6.4  | 5.8  | 5.2  | 5.0  |
| 45                     | 66                                       | 33  | 22  | 17  | 13   | 11   | 9.5  | 8.3  | 7.4  | 6.6  | 6.0  | 5.8  |
| 40                     | 76                                       | 38  | 25  | 19  | 15   | 13   | 11   | 9.5  | 8.4  | 7.6  | 6.9  | 6.6  |
| 35                     | 87                                       | 44  | 29  | 22  | 17   | 14   | 12   | 11   | 9.7  | 8.7  | 7.9  | 7.6  |
| 30                     | 100                                      | 50  | 33  | 25  | 20   | 17   | 14   | 12   | 11   | 10   | 9.1  | 8.7  |
| 25                     | 115                                      | 57  | 38  | 29  | 23   | 19   | 16   | 14   | 13   | 12   | 10   | 10   |
| 20                     | 134                                      | 67  | 44  | 33  | 27   | 22   | 19   | 17   | 15   | 13   | 12   | 12   |
| 15                     | 157                                      | 79  | 52  | 39  | 31   | 26   | 22   | 20   | 17   | 16   | 14   | 14   |
| 10                     | 191                                      | 95  | 64  | 48  | 38   | 32   | 27   | 24   | 21   | 19   | 17   | 17   |
| 9                      | 200                                      | 100 | 66  | 50  | 40   | 33   | 28   | 25   | 22   | 20   | 18   | 17   |
| 8                      | 209                                      | 105 | 70  | 52  | 42   | 35   | 30   | 26   | 23   | 21   | 19   | 18   |
| 7                      | 220                                      | 110 | 74  | 55  | 44   | 37   | 32   | 28   | 24   | 22   | 20   | 19   |
| 6                      | 233                                      | 117 | 78  | 58  | 47   | 39   | 33   | 29   | 26   | 23   | 21   | 20   |
| 5                      | 248                                      | 124 | 83  | 62  | 50   | 41   | 35   | 31   | 28   | 25   | 23   | 22   |
| 4                      | 267                                      | 133 | 89  | 67  | 53   | 44   | 38   | 33   | 30   | 27   | 24   | 23   |
| 3                      | 291                                      | 145 | 97  | 73  | 58   | 48   | 42   | 36   | 32   | 29   | 26   | 25   |
| 2                      | 324                                      | 162 | 108 | 81  | 65   | 54   | 46   | 40   | 36   | 32   | 30   | 28   |
| 1                      | 382                                      | 191 | 127 | 95  | 76   | 64   | 54   | 48   | 42   | 38   | 35   | 33   |
| 0.5                    | 439                                      | 220 | 146 | 110 | 88   | 73   | 63   | 55   | 49   | 44   | 40   | 38   |
| 0.1                    | 572                                      | 286 | 191 | 143 | 114  | 95   | 82   | 72   | 64   | 57   | 52   | 50   |
| 0.01                   | 763                                      | 382 | 254 | 191 | 153  | 127  | 109  | 95   | 85   | 76   | 69   | 66   |

Note: Data were obtained using equation 3 and mean experimental values.

Appendix 15. Sample of a data sheet used for the experiments on solar dechlorination (halosol technique) of water exposed in a continuous-flow system.

| Experiment No. <u>4</u> Solar Reactor: <u>1A</u>                                    |                 |                     |                               |                               |                                  |                                  |                                       |  |  |
|-------------------------------------------------------------------------------------|-----------------|---------------------|-------------------------------|-------------------------------|----------------------------------|----------------------------------|---------------------------------------|--|--|
| Date: <u>6 May 1986</u>                                                             |                 |                     |                               |                               |                                  |                                  |                                       |  |  |
| Initial chlorine residual (mg/L): <u>6.48</u>                                       |                 |                     |                               |                               |                                  |                                  |                                       |  |  |
| Sky conditions: clear <u>—</u> hazy <u>x</u> partly cloudy <u>—</u> cloudy <u>—</u> |                 |                     |                               |                               |                                  |                                  |                                       |  |  |
| Time of day                                                                         | Solar UV-A      |                     |                               |                               | Chlorine residual                |                                  |                                       |  |  |
|                                                                                     | Flow rate (L/h) | Exposure time (min) | Intensity (W/m <sup>2</sup> ) | Fluence (W h/m <sup>2</sup> ) | Influent (C <sub>i</sub> , mg/L) | Effluent (C <sub>e</sub> , mg/L) | C <sub>e</sub> / C <sub>i</sub> x 100 |  |  |
| 7:57                                                                                | 11.69           | 25                  | 3.25                          | 1.35                          | 6.48                             | 2.50                             | 38.58                                 |  |  |
| 8:27                                                                                | 10.23           | 29                  | 4.40                          | 2.13                          | 6.48                             | 2.15                             | 33.18                                 |  |  |
| 8:48                                                                                | 10.23           | 29                  | 5.49                          | 2.65                          | 6.40                             | 2.00                             | 31.40                                 |  |  |
| 9:17                                                                                | 10.20           | 29                  | 7.09                          | 3.43                          | 6.40                             | 1.68                             | 26.25                                 |  |  |
| 9:45                                                                                | 10.50           | 28                  | 9.30                          | 4.34                          | 6.40                             | 1.15                             | 17.97                                 |  |  |
| 10:45                                                                               | 10.27           | 28                  | 14.65                         | 6.84                          | 6.32                             | 0.73                             | 11.55                                 |  |  |
| 11:45                                                                               | 10.54           | 28                  | 19.20                         | 8.96                          | 6.32                             | 0.55                             | 8.70                                  |  |  |
| 12:45                                                                               | 10.54           | 28                  | 20.80                         | 9.70                          | 6.32                             | 0.30                             | 4.75                                  |  |  |
| 13:45                                                                               | 10.40           | 28                  | 18.45                         | 8.60                          | 6.32                             | 0.32                             | 5.06                                  |  |  |
| 14:20                                                                               | 10.40           | 28                  | 14.20                         | 6.63                          | 6.00                             | 0.40                             | 6.67                                  |  |  |
| 14:45                                                                               | 10.36           | 28                  | 13.33                         | 6.22                          | 6.00                             | 0.45                             | 7.50                                  |  |  |
| 15:20                                                                               | 10.37           | 28                  | 11.95                         | 5.58                          | 6.00                             | 0.40                             | 6.67                                  |  |  |
| 15:40                                                                               | 10.35           | 28                  | 10.13                         | 4.73                          | 6.00                             | 0.58                             | 9.67                                  |  |  |
| Mean ± SD <sup>a</sup>                                                              | 10.47 ±0.38     | 28 ±1               | 11.71 ±5.74                   | 5.48 ±2.68                    | 6.26 ±0.19                       | 1.02 ±0.79                       | 16.00 ±12.10                          |  |  |

<sup>a</sup>SD, standard deviation.

Appendix 16. Summary of experimental mean values for solar dechlorination of water using solar reactors IA and IB.

| Exp. No. | Solar reactor | Date (1986) | Solar UV-A      |                     |                               |                               | Chlorine residual                |                                  |                                       |
|----------|---------------|-------------|-----------------|---------------------|-------------------------------|-------------------------------|----------------------------------|----------------------------------|---------------------------------------|
|          |               |             | Flow rate (L/h) | Exposure time (min) | Intensity (W/m <sup>2</sup> ) | Fluence (W h/m <sup>2</sup> ) | Influent (C <sub>i</sub> , mg/L) | Effluent (C <sub>e</sub> , mg/L) | C <sub>e</sub> / C <sub>i</sub> × 100 |
| 2        | IA            | 21 April    | 3.97            | 74                  | 6.2                           | 7.6                           | 2.79                             | 0.33                             | 11.28                                 |
| 3        | IA            | 24 April    | 5.67            | 52                  | 20.9                          | 18.0                          | 3.66                             | 0.10                             | 2.75                                  |
| 4        | IA            | 6 May       | 10.47           | 28                  | 11.7                          | 5.5                           | 6.26                             | 1.02                             | 16.00                                 |
| 5        | IA            | 20 May      | 5.28            | 56                  | 17.8                          | 16.4                          | 7.30                             | 0.19                             | 2.63                                  |
| 5        | IB            | 20 May      | 6.97            | 45                  | 16.0                          | 12.0                          | 6.36                             | 0.28                             | 4.46                                  |
| 6        | IA            | 27 May      | 28.64           | 10                  | 19.1                          | 3.2                           | 4.70                             | 1.82                             | 38.68                                 |
| 7        | IB            | 13 June     | 21.01           | 15                  | 18.3                          | 4.6                           | 1.46                             | 0.30                             | 20.46                                 |
| 8        | IB            | 24 June     | 20.59           | 15                  | 18.0                          | 4.4                           | 5.88                             | 1.40                             | 23.80                                 |
| 8        | IA            | 24 June     | 19.38           | 15                  | 17.9                          | 4.5                           | 2.78                             | 0.78                             | 28.00                                 |
| 9        | IA            | 26 June     | 15.54           | 19                  | 18.3                          | 5.6                           | 4.36                             | 1.01                             | 23.07                                 |
| 10       | IB            | 1 July      | 15.27           | 20                  | 17.4                          | 6.0                           | 4.09                             | 0.66                             | 16.12                                 |

Appendix 17. Analysis of variance ( $p < 0.001$ ) for the percentage reduction in chlorine residual against solar UV-A fluence.

| Analysis of variance |  | SS     | MS    | df | F     |
|----------------------|--|--------|-------|----|-------|
| Regression           |  | 1197.9 | 598.9 | 2  | 53.52 |
| Residual             |  | 89.5   | 11.2  | 8  |       |

Note: SS, sum of squares; MS, mean square; df, degrees of freedom.

Appendix 18. Calculated values for sunlight exposure time (min) at specified solar UV-A intensities as a function of the remaining chlorine residual.

| Remaining chlorine residual <sup>a</sup> (%) | Solar UV-A intensity (W/m <sup>2</sup> ) |     |     |     |      |      |      |      |      |      |      |      |
|----------------------------------------------|------------------------------------------|-----|-----|-----|------|------|------|------|------|------|------|------|
|                                              | 2.0                                      | 4.0 | 6.0 | 8.0 | 10.0 | 12.0 | 14.0 | 16.0 | 18.0 | 20.0 | 22.0 | 24.0 |
| 95                                           | 6.0                                      | 3.0 | 2.0 | 1.5 | 1.2  | 1.0  | 0.9  | 0.8  | 0.7  | 0.6  | 0.5  | 0.5  |
| 90                                           | 13                                       | 6.4 | 4.3 | 3.2 | 2.6  | 2.2  | 1.8  | 1.6  | 1.4  | 1.3  | 1.2  | 1.1  |
| 85                                           | 20                                       | 10  | 6.7 | 5.0 | 4.0  | 3.4  | 2.9  | 2.5  | 2.2  | 2.0  | 1.8  | 1.7  |
| 80                                           | 28                                       | 14  | 9.2 | 6.9 | 5.5  | 4.6  | 3.9  | 3.4  | 3.1  | 2.8  | 2.5  | 2.3  |
| 75                                           | 36                                       | 18  | 12  | 8.9 | 7.1  | 6.0  | 5.1  | 4.5  | 4.0  | 3.6  | 3.2  | 3.0  |
| 70                                           | 44                                       | 22  | 15  | 11  | 8.9  | 7.4  | 6.3  | 5.6  | 4.9  | 4.4  | 4.0  | 3.7  |
| 65                                           | 54                                       | 27  | 18  | 13  | 11   | 9.0  | 7.7  | 6.7  | 6.0  | 5.4  | 4.9  | 4.5  |
| 60                                           | 64                                       | 32  | 21  | 16  | 13   | 11   | 9.0  | 8.0  | 7.1  | 6.4  | 5.8  | 5.3  |
| 55                                           | 75                                       | 37  | 25  | 19  | 15   | 12   | 11   | 9.3  | 8.3  | 7.5  | 6.8  | 6.2  |
| 50                                           | 87                                       | 43  | 29  | 22  | 17   | 14   | 12   | 11   | 9.6  | 8.7  | 7.9  | 7.2  |
| 45                                           | 100                                      | 50  | 33  | 25  | 20   | 17   | 14   | 12   | 11   | 10   | 9.1  | 8.4  |
| 40                                           | 115                                      | 57  | 38  | 29  | 23   | 19   | 16   | 14   | 13   | 12   | 10   | 9.6  |
| 35                                           | 132                                      | 66  | 44  | 33  | 26   | 22   | 19   | 16   | 15   | 13   | 12   | 11   |
| 30                                           | 151                                      | 76  | 50  | 38  | 30   | 25   | 22   | 19   | 17   | 15   | 14   | 13   |
| 25                                           | 174                                      | 87  | 58  | 44  | 35   | 29   | 25   | 22   | 19   | 17   | 16   | 14   |
| 20                                           | 202                                      | 100 | 67  | 50  | 40   | 34   | 29   | 25   | 22   | 20   | 18   | 17   |
| 15                                           | 238                                      | 119 | 80  | 60  | 48   | 40   | 34   | 30   | 26   | 24   | 22   | 20   |
| 10                                           | 290                                      | 145 | 97  | 72  | 58   | 48   | 40   | 36   | 32   | 29   | 26   | 24   |
| 9                                            | 303                                      | 150 | 100 | 76  | 60   | 50   | 43   | 38   | 34   | 30   | 28   | 25   |
| 8                                            | 317                                      | 159 | 106 | 79  | 63   | 53   | 45   | 40   | 35   | 32   | 29   | 26   |
| 7                                            | 334                                      | 167 | 110 | 84  | 67   | 56   | 48   | 42   | 37   | 33   | 30   | 28   |
| 6                                            | 354                                      | 177 | 118 | 88  | 70   | 59   | 50   | 44   | 39   | 35   | 32   | 29   |
| 5                                            | 377                                      | 188 | 126 | 94  | 75   | 63   | 54   | 47   | 42   | 38   | 34   | 30   |
| 4                                            | 405                                      | 202 | 135 | 100 | 80   | 67   | 58   | 50   | 45   | 40   | 37   | 34   |
| 3                                            | 440                                      | 220 | 147 | 110 | 88   | 74   | 63   | 55   | 49   | 44   | 40   | 37   |
| 2                                            | 492                                      | 246 | 164 | 123 | 98   | 82   | 70   | 62   | 55   | 49   | 45   | 40   |
| 1                                            | 579                                      | 290 | 193 | 145 | 116  | 97   | 83   | 72   | 64   | 58   | 53   | 48   |
| 0.5                                          | 667                                      | 333 | 222 | 167 | 133  | 110  | 95   | 83   | 74   | 67   | 60   | 56   |
| 0.1                                          | 869                                      | 436 | 290 | 217 | 174  | 145  | 124  | 109  | 97   | 87   | 79   | 72   |
| 0.01                                         | 1 160                                    | 580 | 385 | 290 | 232  | 193  | 166  | 145  | 129  | 116  | 105  | 97   |

Note: Data were obtained using equation 10 and mean experimental values.

<sup>a</sup>Initial chlorine residuals concentration was 1.5-7.5 mg/L.



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